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NASA CR-2005

EVALUATION OF DRILLED-BALL BEARINGS AT DN VALUES TO THREE MILLION

II - Experimental Skid Study and Endurance Tests

by P. W. Holmes

Prepared by
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for Lewis Research Center

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16. Abstract

Both drilled- and solid-ball 120-mm-bore bearings were tested at speeds up to 24 000 rpm (3.0 million DN) to determine skid characteristics. The thrust loads were varied from 22 000 newtons (5000 lb) down to 1600 newtons (370 lb). No gross skidding occurred, and the behavior of the two bearing types was generally similar; however, two drilled-ball bearing failures occurred during the skid tests. In the endurance tests, 25 cycles of start, run (for one hour), and stop were completed before a drilled-ball bearing failed. In all three cases, the ball had failed in flexure fatigue.

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EVALUATION OF DRILLED-BALL BEARINGS AT DN VALUES TO THREE MILLION

II - EXPERIMENTAL SKID STUDY AND ENDURANCE TESTS

INTRODUCTION

A recognized need exists in the aircraft gas turbine industry for rolling element bearings having significantly increased speed capability. The successful development of projected engines depends, in part, upon the development of bearings having nearly twice the speed capabilities of those now in use. Current production engines operate in the range of 1.5 to 1.9 million DN (bearing bore in millimeters X rpm), while engines now under development operate at DN values from 2.0 to 2.5 million DN. Engines presently in the conceptual stage will require mainshaft bearing speed capability of 3.0 million DN or greater.

One approach to higher bearing speeds is to reduce the mass of the rolling elements by various hollowing techniques. This reduces the centrifugal load these elements apply to their outer races and may be expected to lead to increased fatigue life at high speeds. Considerable success has been had with hollow roller bearings, and the related "drilled-ball" concept has shown distinct promise in preliminary testing of ball-thrust bearings to speeds of 3.0 million DN.

The experience accumulated by NASA-Lewis Research Center and by Pratt & Whitney Aircraft under Contract NAS3-13491 showed that drilled-ball bearings operate with somewhat lower outer-race temperatures than equivalent solid-ball bearings, at the same conditions of load, speed, oil flow, and oil supply temperature. At the conclusion of Contract NAS3-13491, it was apparent that further exploration and development of drilled-ball bearings was warranted to more fully define their operational characteristics and limits. As a result, the present program was initiated under Contract NAS3-14417 to obtain additional performance data with drilled-ball bearings over an expanded range of test operating conditions, using equivalent solid-ball bearings as a baseline reference. The necessary baseline and drilled-ball bearings were procured and initially tested under Contract NAS3-13491 and required only cage replating and balancing to be suitable for further testing.

This program consists of four distinct tasks, outlined as follows:

Task I	Bearing refurbishment and calibraiton of the test rig's oil transfer scoops
Task II	Comparison of solid-ball and drilled-ball bearing behavior over a range of oil supply flows
Task III	Comparison of solid-ball and drilled-ball bearing responses to skidding conditions
Task IV	Investigation of drilled-ball bearing durability in cyclic operation

The work done under Tasks I and II was reported in the first topical report (PWA-4235). The Task II work, in particular, provided a basis for selecting the bearing oil flow rate used for Task III and Task IV testing.

This report describes the solid-ball and drilled-ball bearing configurations, discusses test equipment and techniques, and summarizes the test results obtained in Task III and Task IV.

SUMMARY

The bearings tested under Contract NAS3-13491 were made suitable for further testing under the present contract by simply replating and rebalancing the bearing cages. Calibration of the test rig's two oil-transfer scoops in Task I revealed that their performances were identical, with a nominal scoop efficiency of 76% ± 3% at most combinations of shaft speed and oil supply flow. In Task II, two solid-ball bearings and two drilled ball bearings were tested at oil flow rates ranging from 45.4 x 10^{-3} kilograms per second (6 lb/min) per bearing to 121 x 10^{-3} kilograms per second (16 lb/min) per bearing at bearing speeds from 1.0 million DN to 3.0 million DN. On the basis of this work, which is described in detail in the first topical report (Report PWA-4235), an oil flow rate of 121 x 10^{-3} kilograms per second (16 lb/min) per bearing was selected for the Task III and Task IV testing described in this report.

Under Task III, comparative skid-mapping tests were conducted on solid-ball and drilled-ball bearings at 366.5°K (200°F) and at 388.7°K (240°F) oil supply temperatures, at bearing speeds from 1.0 million DN to 3.0 million DN. The skid behavior of the two bearing configurations was generally similar. Neither configuration showed positive skidding tendencies at speeds of 2.4 million DN or less at either of the two oil supply temperatures. Both configurations showed some skid tendency at very high speeds although this was limited to a reduction in cage speed of only about 2% and occurred, in each instance, in a very small range of thrust load. Definite skid behavior was first observed in both configurations at 2.8 million DN at the two oil supply temperatures. There was some indication that the drilled-ball bearings were slightly more sensitive to skidding than the solid ball bearings although neither configuration showed strong skidding tendencies.

Evidence of pin wear after testing of the drilled bearings at maximum load, minimum speed conditions in Task III showed that the drilled-balls were tilting at least 30 degrees at that condition. This correlates with analytical predictions of ball tilting and indicates a potential design boundary condition for bearings of this type. Two drilled-ball fatigue failures were experienced in the course of Task III. The maximum thrust load was reduced from 22,241 newtons (5000 lb) to 13,344 newtons (3000 lb) after the first failure. The second failure occurred at a moderate thrust load, but the bearing had experienced the same amount of testing at 22,241 newtons (5000 lb) as the first bearing to fail.

Under Task IV, cyclic tests were conducted simultaneously on one solid-ball bearing and one drilled-ball bearing operating in the same rig. Each test cycle consisted of starting up from zero speed to 2.6 million DN according to a specified schedule of speed and load, operating for an hour at 2.6 million DN and a thrust load of 13,344 newtons (3000 lb) and then shutting down according to a specified schedule. Twenty-five such cycles were completed, with the test terminating when abnormalities were observed in the drilled-ball bearing data at the end of the twenty-fifth cycle. It was found that a drilled ball had failed in fatigue. Inspection revealed that the drilled balls had not excessively or roughly contacted the circumferential surfaces of the restraining pins during the startup and shutdown sequences of each endurance cycle.

CONCLUSIONS AND RECOMMENDATIONS

There are three principal conclusions to be drawn from this work, as follows:

1. The skid behavior of drilled-ball bearings is very similar in character to that of the solid-ball bearings from which they were derived. The drilled-ball bearings have some tendency to skid at slightly lower speeds and slightly higher loads than the solid-ball bearings, but both configurations proved relatively insensitive to skidding at the oil flow rate and oil supply temperatures at which these tests were conducted.

2. The three drilled-ball fatigue failures experienced in the course of Tasks III and IV indicate that the drilled-ball design used in these tests is load limited.

3. The balls in the drilled-ball bearings used in this program reached their maximum tilt angle at 30° at a speed-load combination of 1.0 million DN and 22,241 newtons(5000 lbs). This is a function of the specific design, and is not a generalized limitation. However, experience with these bearings under Contract NAS3-13491 indicated that ball tilting and yawing permitted by the ball/pin geometry was about the maximum acceptable for very low speed operation during start-up. It is concluded that there may be distint geometrical constraints which should be observed in design of a drilled-ball bearing.

On the basis of these conclusions, it is recommeded that specific detailed attention be given to ball design and test with the objective of demonstrating increased load and fatigue life capabilities in drilled-ball configurations. It is recommended, also, that parallel efforts be made to define the geometrical constraints under which a drilled ball must operate, and the effect of principal bearing design parameters on those constraints, so that the improved drilled-ball geometry will be fully compatible with bearing requirements.

TEST BEARINGS

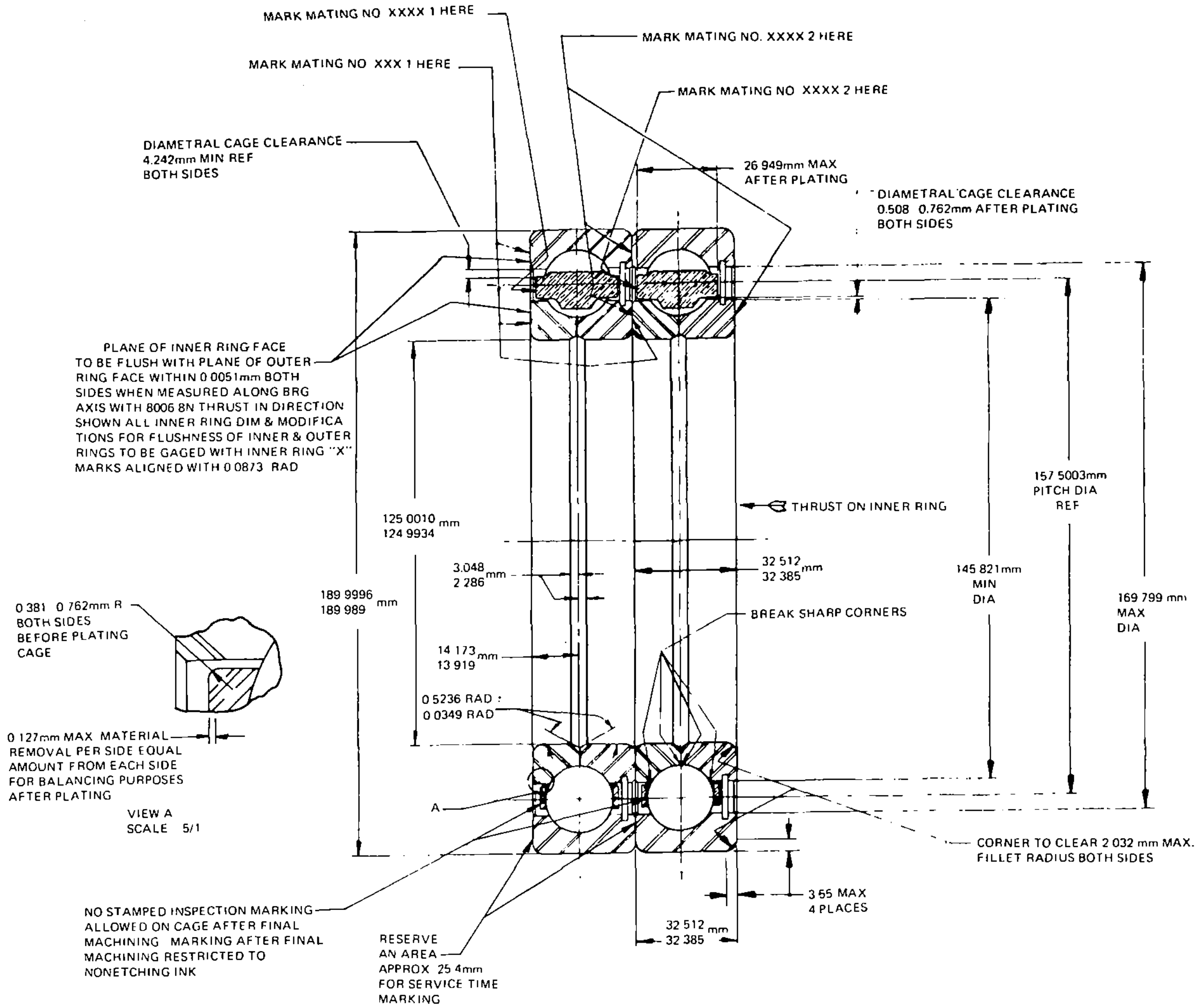
The test bearings utilized in this contract were procured and initially tested at up to 3.0 million DN under Contract NAS3-13491. The bearings were in good condition after these tests and required only replating and rebalancing of the cages to be suitable for continued testing under the present contract.

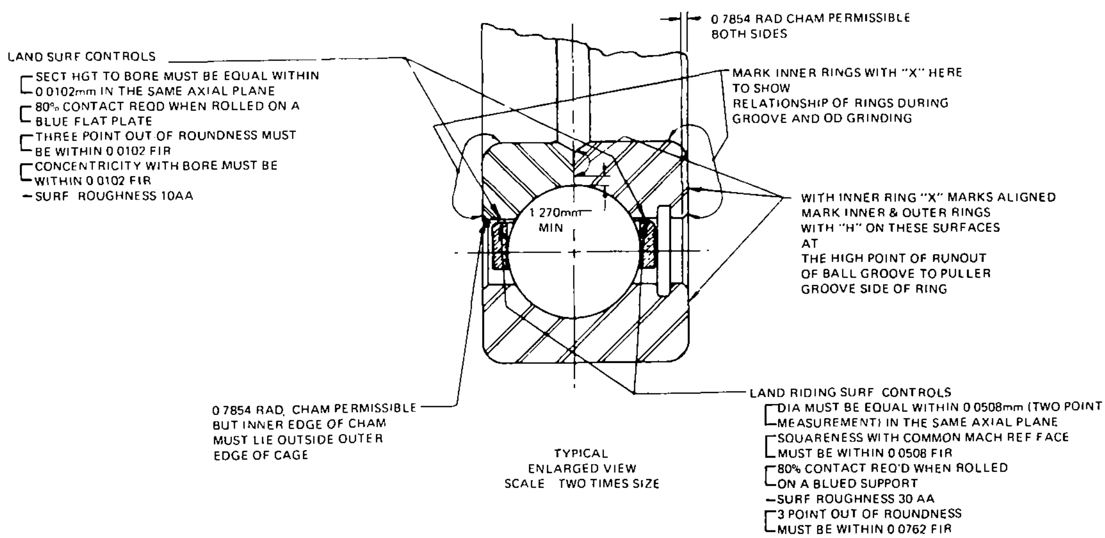
The test bearings were derived from a basic bearing which has been used extensively in a production aircraft engine. The basic bearing is used in pairs to form a duplex thrust bearing in its engine application, as indicated in Figures 1 and 1A. The basic bearing has a bore of 125 mm, a ball diameter of 20.6375 mm (0.8125 in.), a split inner ring, and a one-piece cage which rides on two inner lands. The balls and rings are made of M-50 CVM steel, hardened to Rockwell C60 minimum. The cage is made of AMS 6415 steel, hardened to Rockwell C28-32 and silver plated. The contact angle is 0.4014-0.4538 radians (23-26 degrees) under static conditions with a thrust load of 266.9 newtons (60 pounds). When the bearing is assembled, recesses in the mating surfaces of the two inner rings form lubricant passages between the bearing ID and the inner-race surface. The bearing is made to ABEC 7 and is manufactured by the Marlin-Rockwell Company.

The basic bearing was designed for normal service at about 1.5 million DN, and two modifications were required to ensure satisfactory operation at speeds up to 3.0 million DN. The first modification consisted of installing additional oil passages to the inner rings to improve ring-to-cage lubrication. These passages are shown in Figures 2 and 3. The second modification increased ball pocket diameter to the dimensions shown in Figure 4. This modification minimizes rubbing between the cage and inner rings due to drag caused by restricted ball travel within the cage pocket.

Under Contract NAS3-13491, eight bearings had been modified in accordance with Figures 2, 3, and 4. Four of these modified bearings were used for baseline testing. The remaining four had been altered further to a drilled-ball configuration in which the ball mass was reduced by approximately 50 percent and stub pins had been installed in the cage to prevent the drilled balls from presenting their edges to the bearing races. The ball modifications are shown in Figure 5. Details of the restraining pins are shown in Figure 6, and modifications made in the cage rails to accept the pins are shown in Figure 7. The appearance of the drilled balls and the cages with pins installed is shown in Figures 8 and 9, respectively.

All eight test bearings were in good condition after the testing done under Contract NAS3-13491 and required only replating and rebalancing of the cages to be suitable for continued testing under the present contract. Two of the solid-ball bearings and two of the drilled-ball bearings were used in Task II. The two remaining solid-ball bearings and three of the drilled-ball bearings were used, in the course of Tasks III and IV.





TYPICAL
ENLARGED VIEW
SCALE TWO TIMES SIZE

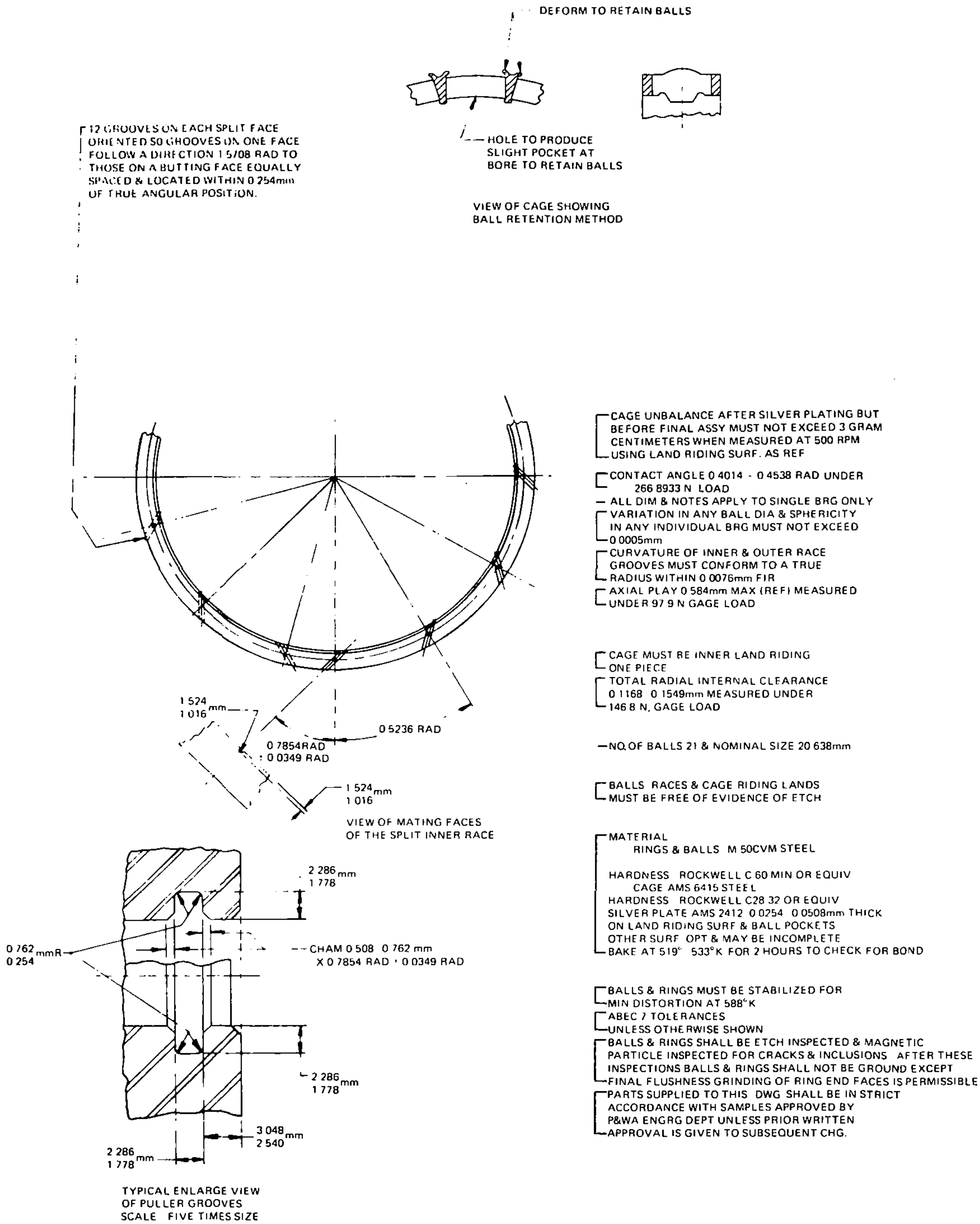
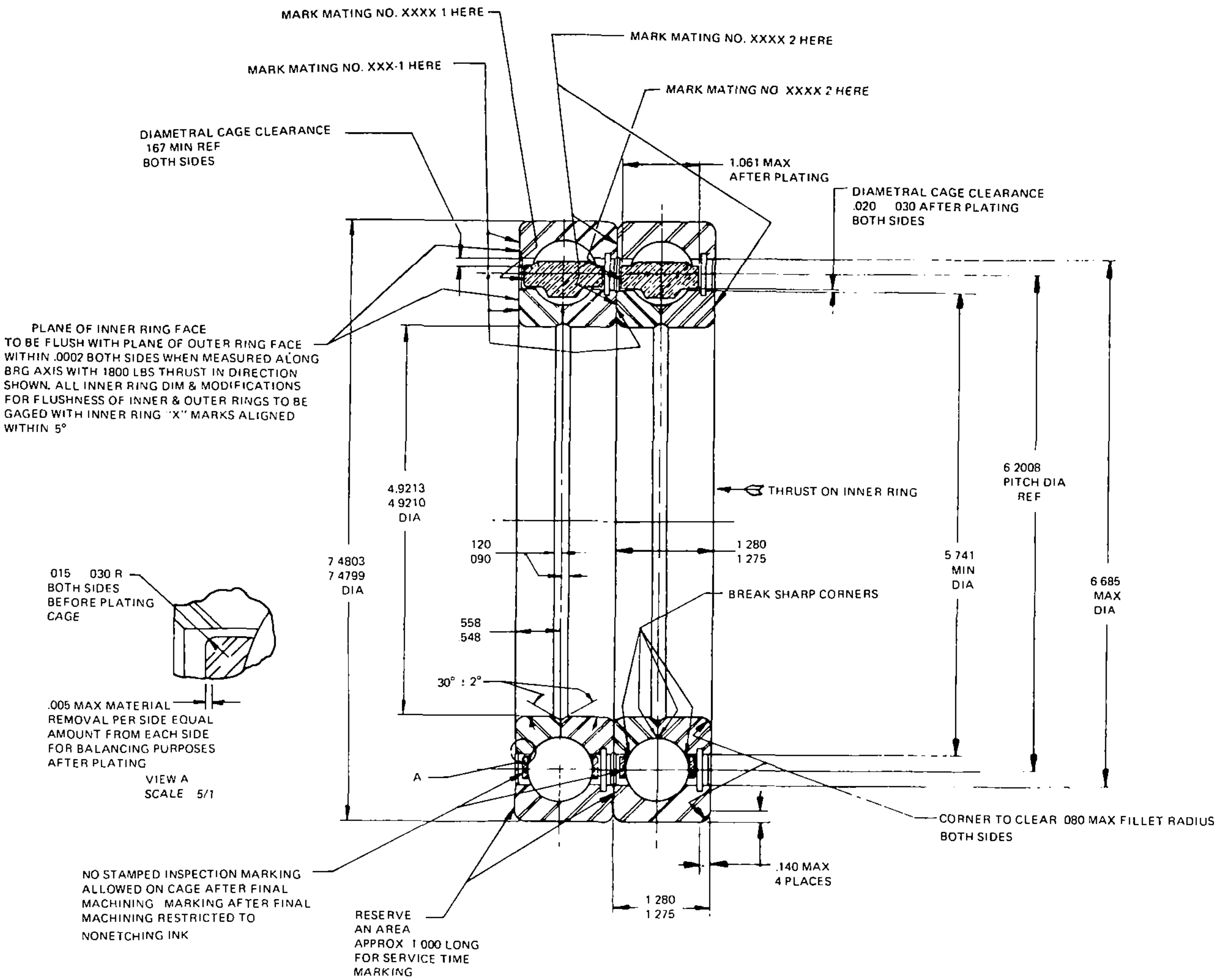
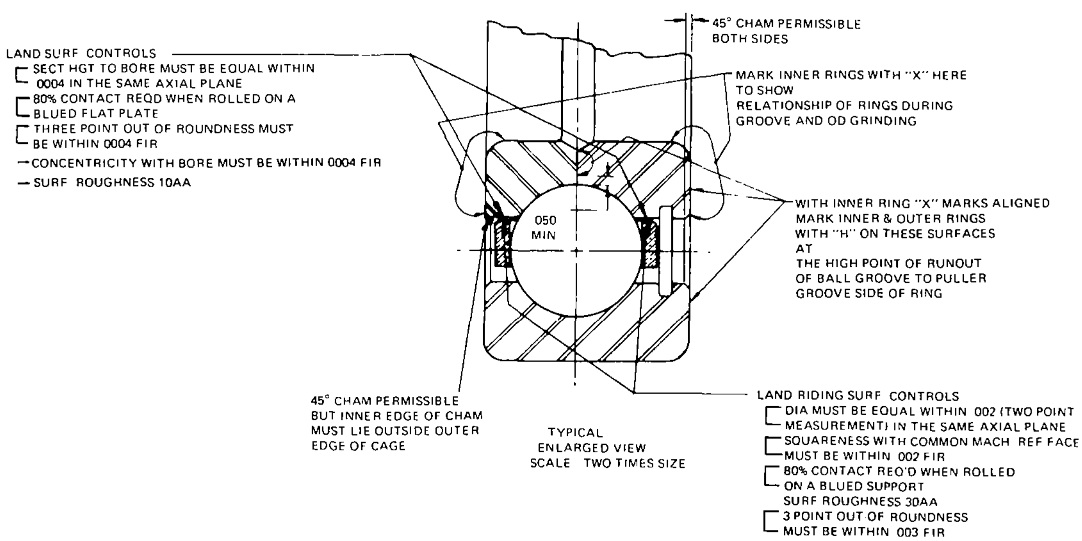


Figure 1
Specification Drawing for Selected Bearing
(Dimensions in millimeters unless otherwise noted)


MARK MATING NO. XXXX 1 HERE
MARK MATING NO. XXXX 2 HERE
MARK MATING NO. XXX-1 HERE
MARK MATING NO XXXX 2 HERE
DIAMETRAL CAGE CLEARANCE
167 MIN REF
BOTH SIDES
1.061 MAX
AFTER PLATING
DIAMETRAL CAGE CLEARANCE
.020 030 AFTER PLATING
BOTH SIDES
PLANE OF INNER RING FACE
TO BE FLUSH WITH PLANE OF OUTER RING FACE
WITHIN .0002 BOTH SIDES WHEN MEASURED ALONG
BRG AXIS WITH 1800 LBS THRUST IN DIRECTION
SHOWN. ALL INNER RING DIM & MODIFICATIONS
FOR FLUSHNESS OF INNER & OUTER RINGS TO BE
GAGED WITH INNER RING "X" MARKS ALIGNED
WITHIN 5°
6 2008
PITCH DIA
REF
4.9213
4 9210
DIA
THRUST ON INNER RING
120
090
1 280
1 275
7 4803
7 4799
DIA
5 741
MIN
DIA
6 685
MAX
DIA
015 030 R
BOTH SIDES
BEFORE PLATING
CAGE
BREAK SHARP CORNERS
558
548
30° ± 2°
.005 MAX MATERIAL
REMOVAL PER SIDE EQUAL
AMOUNT FROM EACH SIDE
FOR BALANCING PURPOSES
AFTER PLATING
VIEW A
SCALE 5/1
A
CORNER TO CLEAR 080 MAX FILLET RADIUS
BOTH SIDES
.140 MAX
4 PLACES
NO STAMPED INSPECTION MARKING
ALLOWED ON CAGE AFTER FINAL
MACHINING MARKING AFTER FINAL
MACHINING RESTRICTED TO
NONETCHING INK
RESERVE
AN AREA
APPROX 1 000 LONG
FOR SERVICE TIME
MARKING
1 280
1 275


45° CHAM PERMISSIBLE
BOTH SIDES
LAND SURF CONTROLS
SECT HGT TO BORE MUST BE EQUAL WITHIN
0004 IN THE SAME AXIAL PLANE
80% CONTACT REQD WHEN ROLLED ON A
BLUED FLAT PLATE
THREE POINT OUT OF ROUNDNESS MUST
BE WITHIN 0004 FIR
CONCENTRICITY WITH BORE MUST BE WITHIN 0004 FIR
SURF ROUGHNESS 10AA
MARK INNER RINGS WITH "X" HERE
TO SHOW
RELATIONSHIP OF RINGS DURING
GROOVE AND OD GRINDING
050
MIN
WITH INNER RING "X" MARKS ALIGNED
MARK INNER & OUTER RINGS
WITH "H" ON THESE SURFACES
AT
THE HIGH POINT OF RUNOUT
OF BALL GROOVE TO PULLER
GROOVE SIDE OF RING
45° CHAM PERMISSIBLE
BUT INNER EDGE OF CHAM
MUST LIE OUTSIDE OUTER
EDGE OF CAGE
TYPICAL
ENLARGED VIEW
SCALE TWO TIMES SIZE
LAND RIDING SURF CONTROLS
DIA MUST BE EQUAL WITHIN 002 (TWO POINT
MEASUREMENT) IN THE SAME AXIAL PLANE
SQUARENESS WITH COMMON MACH REF FACE
MUST BE WITHIN 002 FIR
80% CONTACT REQ'D WHEN ROLLED
ON A BLUED SUPPORT
SURF ROUGHNESS 30AA
3 POINT OUT OF ROUNDNESS
MUST BE WITHIN 003 FIR

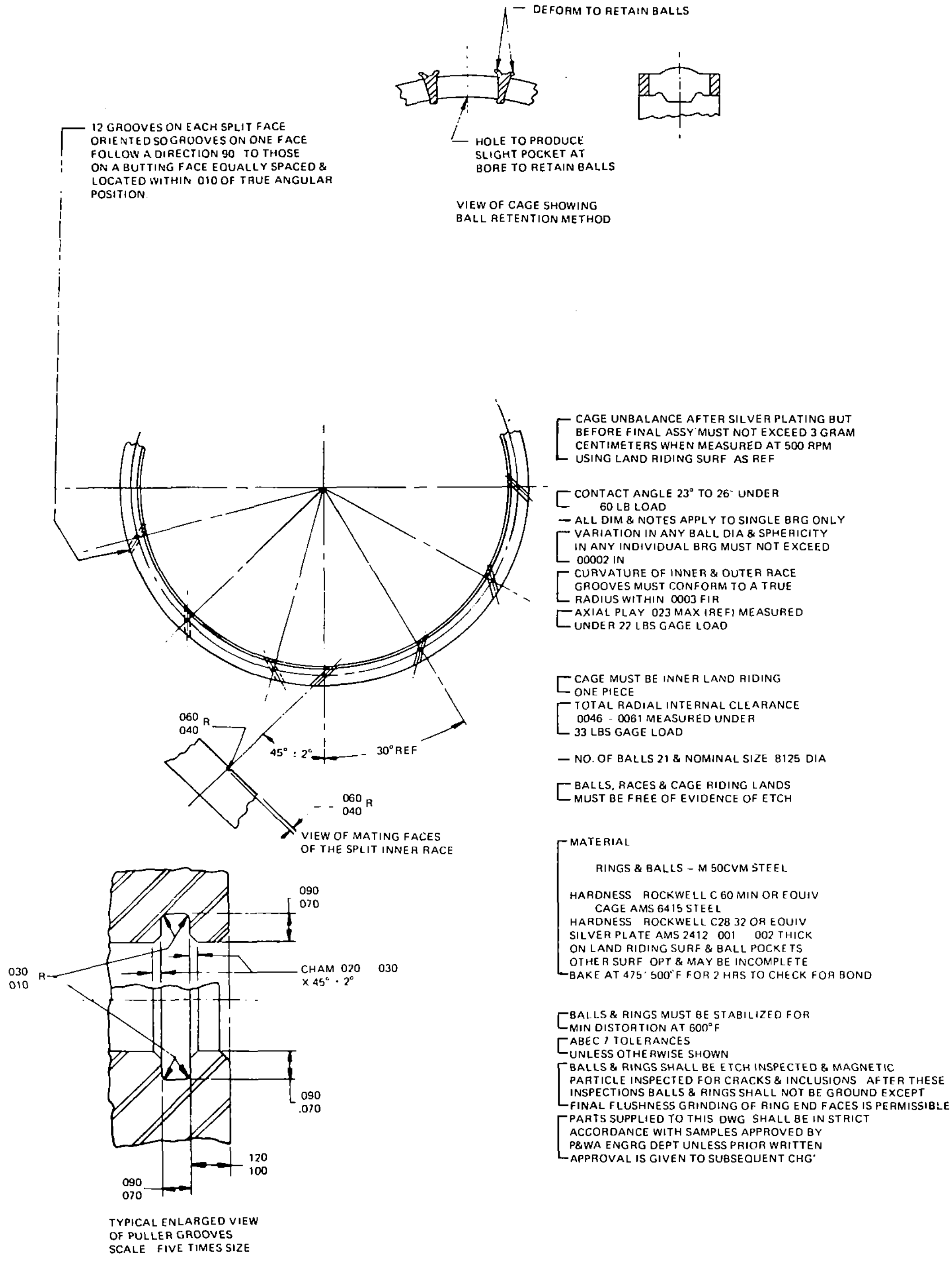


Figure 1A
Specification Drawing for Selected Bearing
(Dimensions in inches unless otherwise noted)

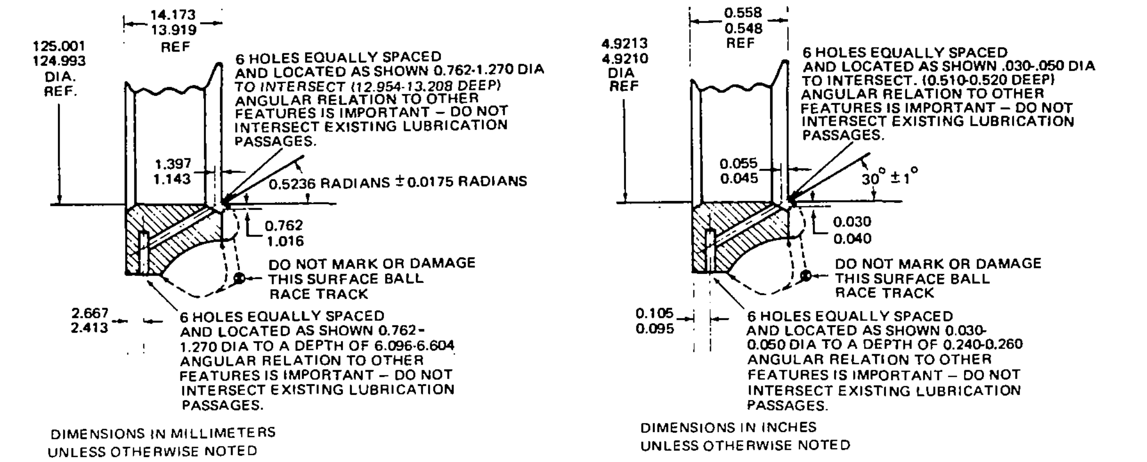


Figure 2 Inner Ring Alteration

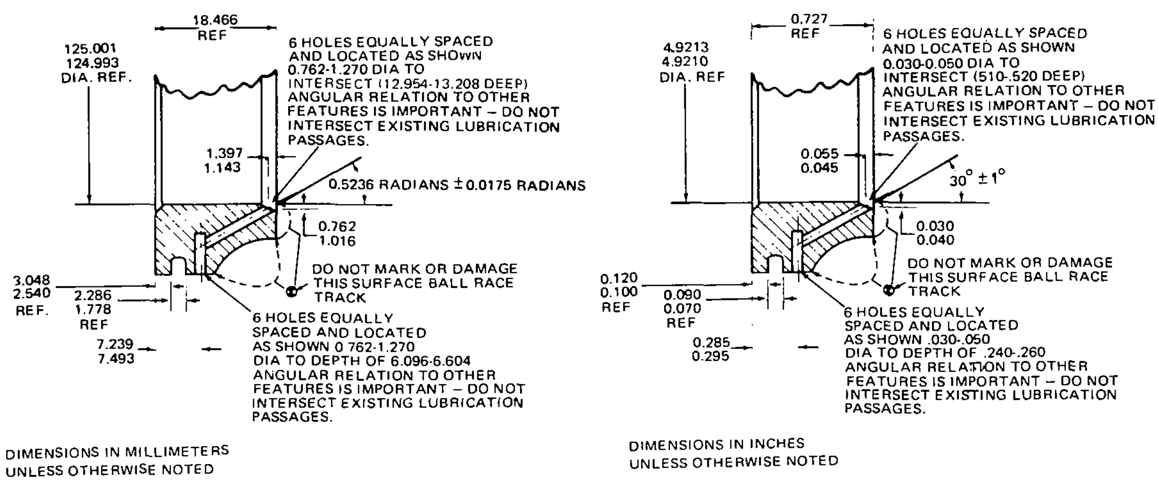
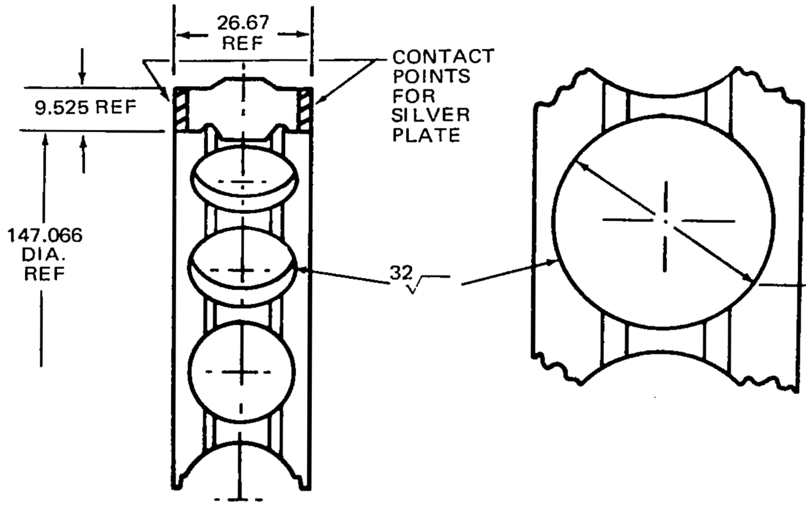


Figure 3 Inner Ring Alteration

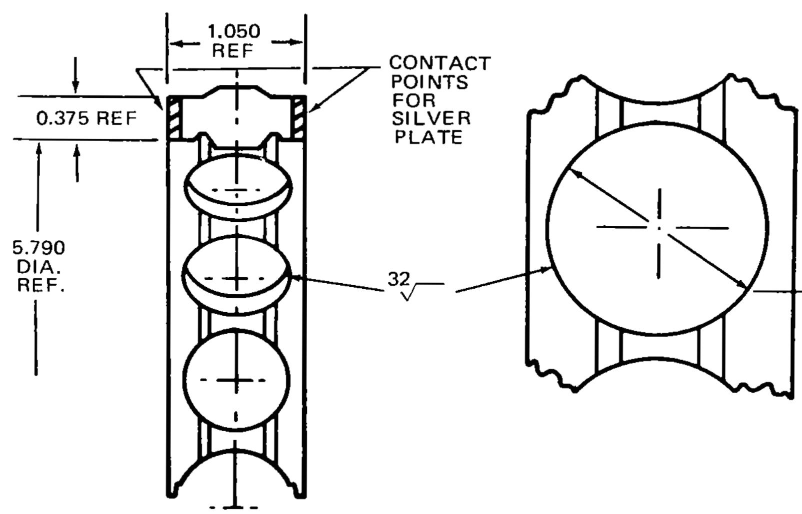


NOTES:
1. MACHINE OPEN 21 BALL POCKETS TO DIA. SHOWN & MAINTAIN A SURFACE-FINISH OF 32√ ON NEW DIA SURFACE.
2. REMOVE SILVER PLATE FROM CAGE.
3. PLATE CAGE PER AMS 2412. BAKE 519°-533°K FOR 2 HRS TO CHECK BOND. PLATE 0.0254-0.0508 THICK ON ID & BALL POCKETS. OTHER SURFACES OPTIONAL.
4. BALANCE CAGE NOT TO EXCEED 3 GRAM CENTIMETERS WHEN MEASURED AT 500 RPM MIN. USING LAND RIDING SURFACE AS REFERENCE.

21.603
21.476 DIA.

21 PLACES
PERMITTED TO
MACHINE OFF
OR THROUGH
RETAINING
TANGS ON OD & ID

DIMENSIONS IN MILLIMETERS
UNLESS OTHERWISE NOTED



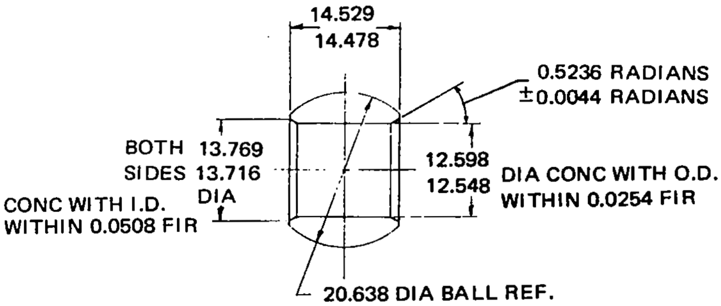
NOTES:
1. MACHINE OPEN 21 BALL POCKETS TO DIA. SHOWN & MAINTAIN A SURFACE-FINISH OF 32√ ON NEW DIA SURFACE
2. REMOVE SILVER PLATE FROM CAGE.
3. PLATE CAGE PER AMS 2412. BAKE 475°-500°F FOR 2 HRS TO CHECK BOND. PLATE .0010 TO .0020 THICK ON ID & BALL POCKETS. OTHER SURFACES OPTIONAL.
4. BALANCE CAGE NOT TO EXCEED 3 GRAM CENTIMETERS WHEN MEASURED AT 500 RPM MIN. USING LAND RIDING SURFACE AS REFERENCE.

0.8505
0.8455 DIA

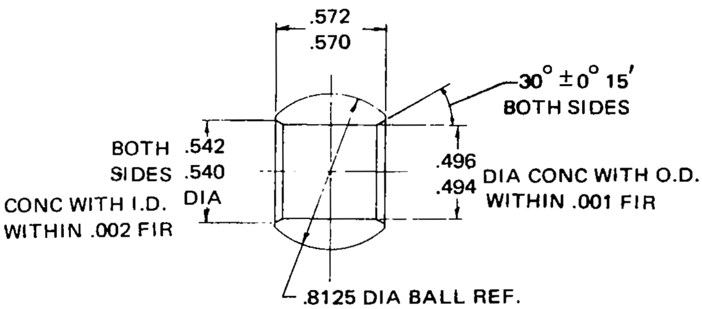
21 PLACES
PERMITTED TO
MACHINE OFF
OR THROUGH
RETAINING
TANGS ON OD & ID

DIMENSIONS IN INCHES
UNLESS OTHERWISE NOTED

Figure 4 Cage Alteration



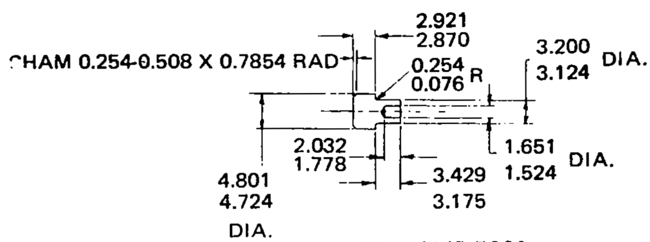
DIMENSIONS IN MILLIMETERS
UNLESS OTHERWISE NOTED



DIMENSIONS IN INCHES
UNLESS OTHERWISE NOTED

Figure 5 Ball Detail

DIMENSIONS IN MILLIMETERS
UNLESS OTHERWISE NOTED



MATL: AMS 7229

DIMENSIONS IN INCHES
UNLESS OTHERWISE NOTED

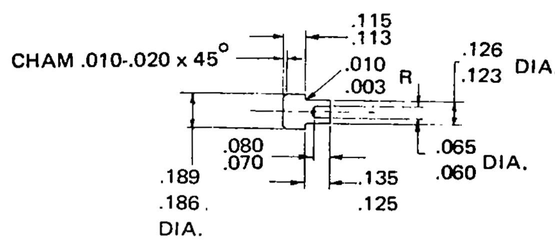


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Figure 6 Pin Detail

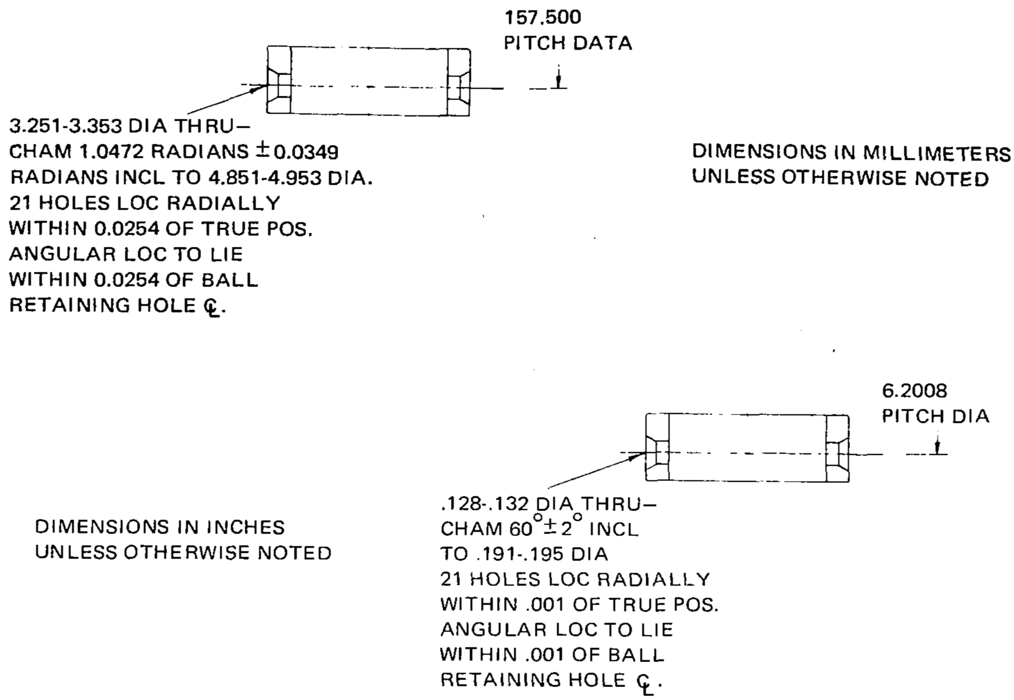


Figure 7 Cage Detail

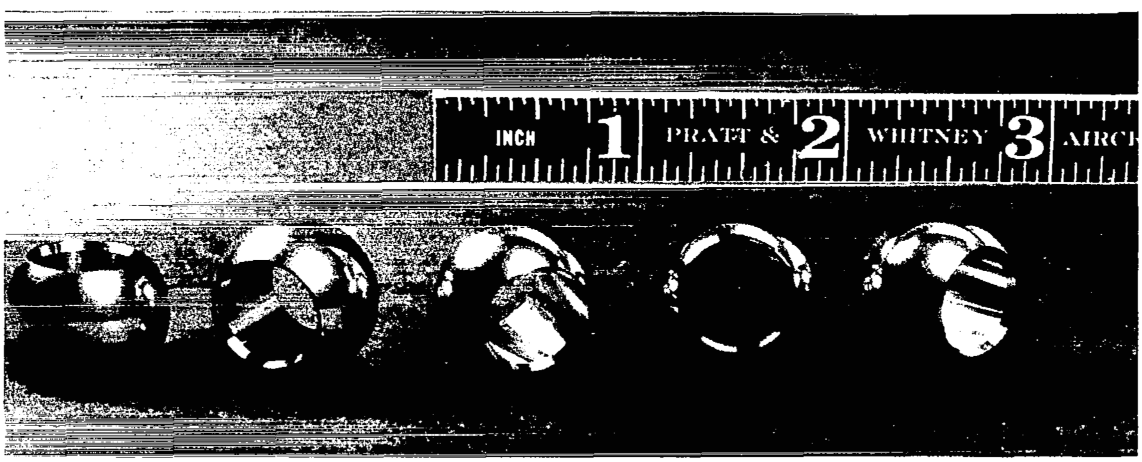


Figure 8 Typical Drilled Balls

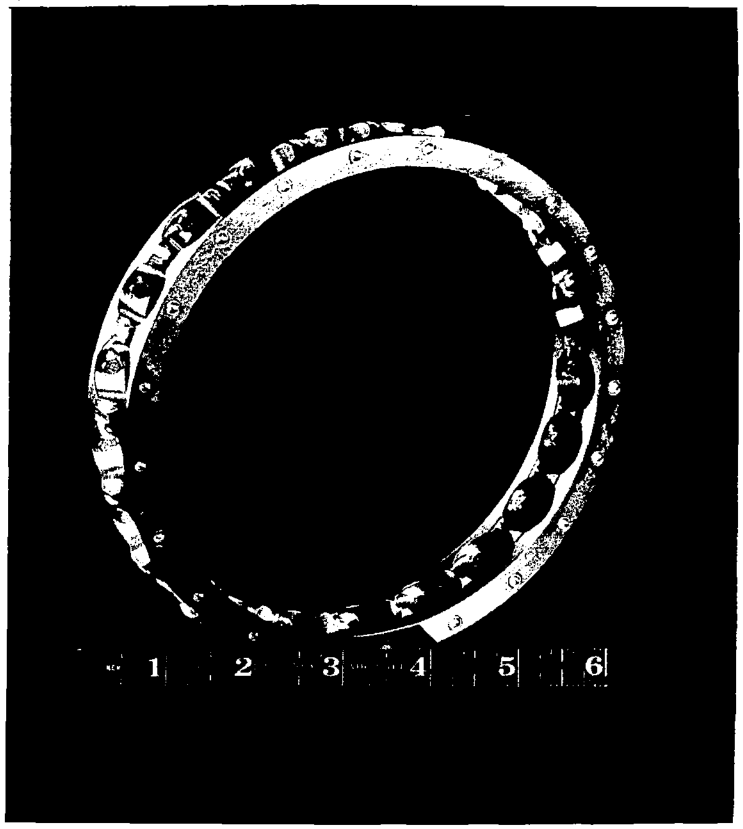


Figure 9 Drilled-Ball Bearing Cage With Pins Installed

TEST EQUIPMENT

Evaluation of the test bearings was carried out in an existing contractor-owned thrust ball bearing rig which had previously demonstrated high DN operational capability. Contractor-owned test stand facilities, which had been used in Contract NAS3-13491, were utilized to produce the operating conditions of the test program. Instrumentation generally used in conventional test practice was employed to measure, monitor, and record test bearing parameters at each operating condition.

BEARING TEST RIG

The bearing test rig, shown in Figure 10, consisted of a cylindrical housing with an annular thrust loading system at one end. Two similar bearings were mounted on a common shaft along with their outer race carriers. This complete assembly was slipped into the cylindrical housing, engaged to a spline on the gearbox drive shaft, and secured with a cover at the front end of the rig. In operation, the hydraulic loading piston applied axial loads to the outer race carrier of the rear bearing. The load was transmitted through the rear bearing to the common shaft, and then through the front bearing to the housing. As a result, two identical bearings were tested simultaneously under identical conditions. The test rig shaft was driven by a variable-speed, 111.9 kilowatt (150 hp) DC electric motor through a 7 to 1 gear speed increaser as shown in Figure 11.

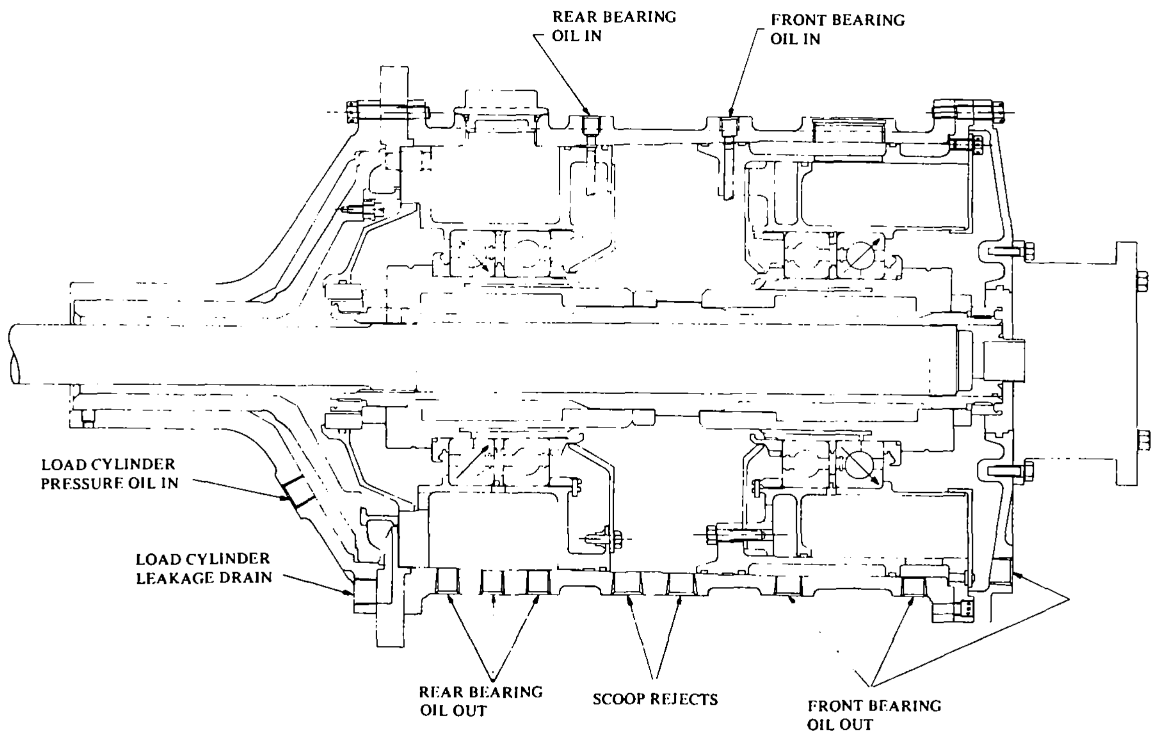


Figure 10 Thrust Bearing Test Rig

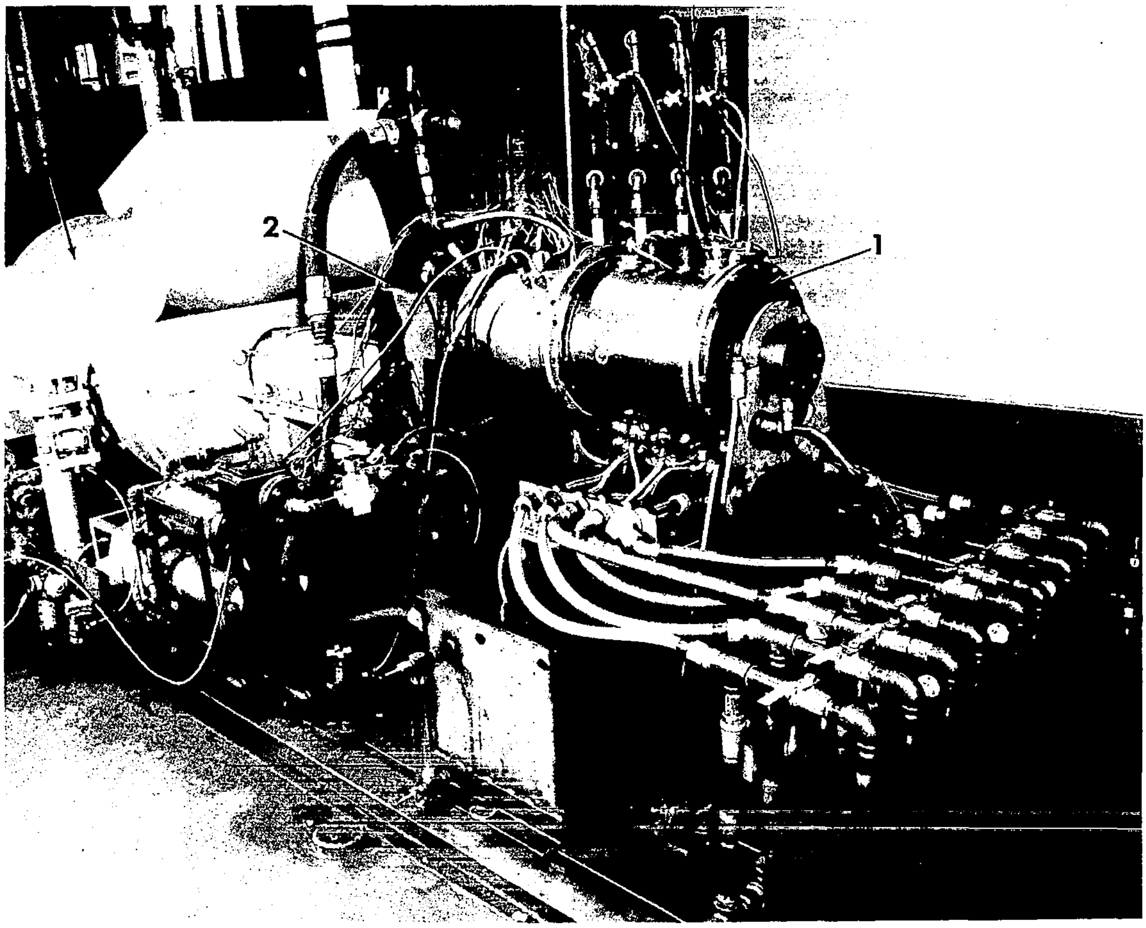
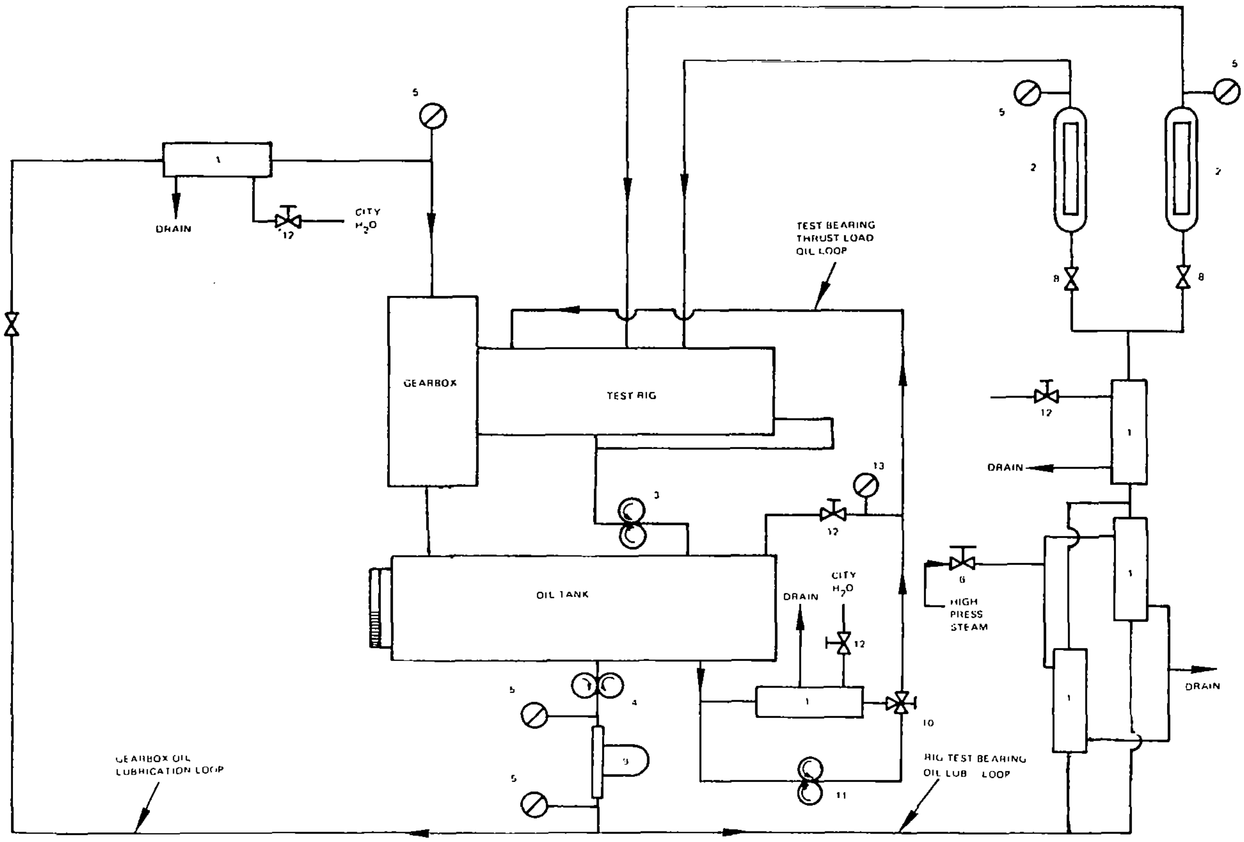


Figure 11 Thrust Bearing Test Rig
(1) Test Rig (2) Gearbox
(3) Electric Drive Motor

LUBRICATION SYSTEM

The relationship between the test rig and the external lubrication system is shown in Figure 12. The complete system consisted of three oil-circulating loops supplied from a common reservoir. One loop lubricated the gearbox for the rig's drive unit. The second loop provided hydraulic pressure for thrust loading the test bearings. The third loop provided lubrication for the test bearings, and contained heat exchangers, instrumentation, and controls necessary for maintaining suitable oil temperatures and flow rates to the test bearings.



1. Heat Exchanger "American Std"
   Series 503, Single Pass

2. Flowmeter "Fisher Porter"
   Model 10A1152AOM, Sign 5

3. Pump "Viking Pump Co"
   No. HL-154, Cap. 11.4 x 10^{-4} m^3/sec (18 gpm)

4. Pump "Viking Pump Co"
   No. 253, Cap. 3.2 x 10^{-4} m^3/sec (5 gpm)

5. Gage "Halicoid"
   Type 440 RH Heliy. Size 4½ 11,
   0-689, 476 N/m^2 (0-100 psi)

6. Control Valve "Jenkins Valve Co"
   No. CF-TM 34-200

7. Pressure Regulating Valve "Cash-Acme"
   Type G-60

8. Valve "March Instrument Co"
   Type 1900 PM-FAA

9. Static Filter "Cuno Co"
   S. S. Metal Mesh, 10 Micron Cap.

10. Pressure Regulating Valve "Cash-Acme"
    Type FR-½ NPT

11. Pump "Viking Pump Co"
    No. FH-54,
    Cap. 1.9 x 10^{-4} m^3/sec (3 gpm)

12. Control Valve "Masoneilan"
    No. DR38-26471

13. Gage "Heise"
    Type H470, 8½ Size
    0-861.845 N/m^2 (0-125 psi)

Figure 12 Lubrication System

TEST BEARING LUBRICATION

The method of supplying lubricant to each bearing is shown in Figure 13. Lubricant from the external reservoir was directed by a fixed nozzle into an annular scoop which rotated with the bearing shaft assembly. The lubricant then flowed from the scoop through axially oriented passages in the hub assembly to radial passages terminating at the bearing bore. Lubricant discharged from the test bearings was collected in manifolds at the bottom of the test rig and returned to the external system.

The test bearings were lubricated through a number of passages which originated at the bearing ID. Twenty-four passages led directly from the bearing bore to the inner-race surface along the parting plane of the split inner ring. Each inner ring had six additional passages leading from the bore to the land surface on which the cage rides. This combination of passages provided lubricant directly to the balls and to the cage riding-surfaces.

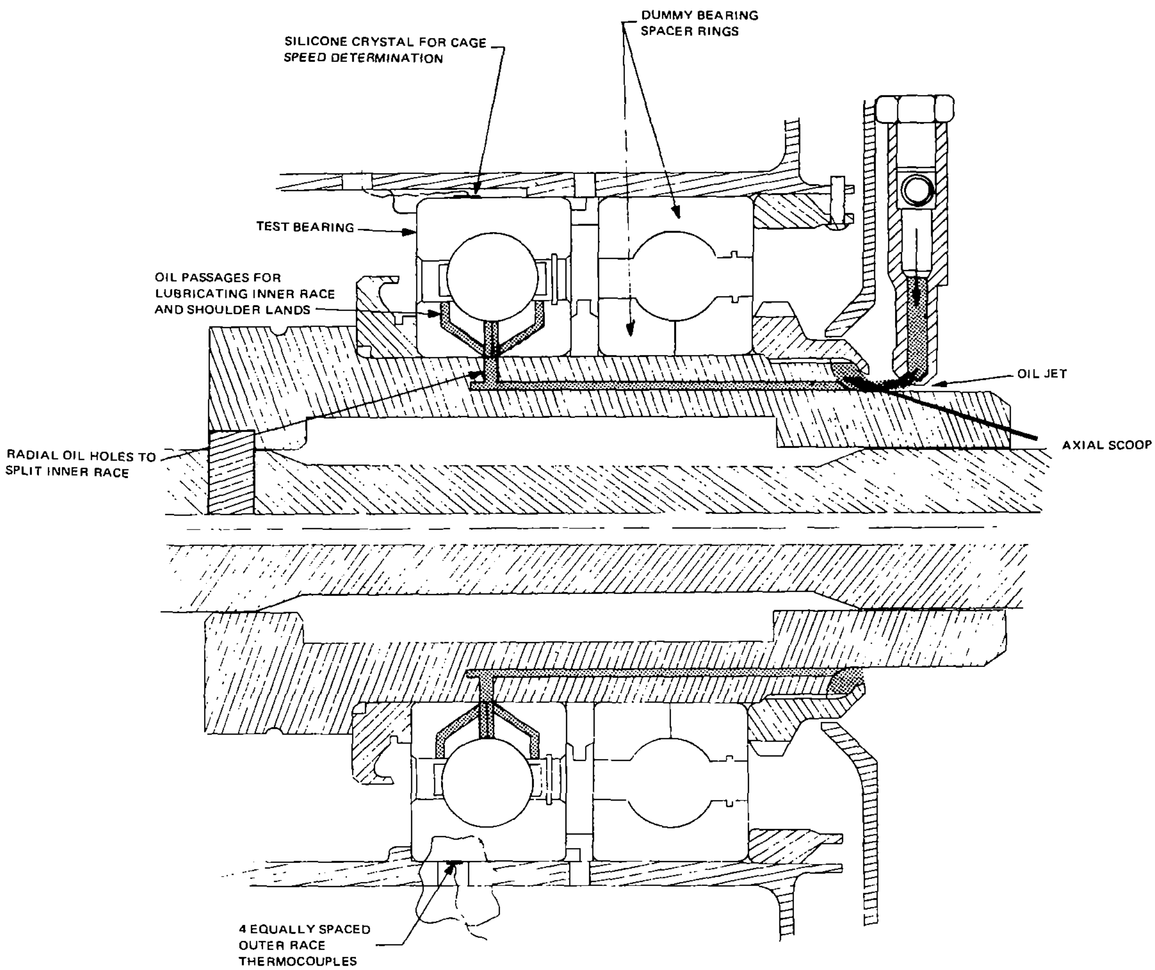


Figure 13 Bearing Lubrication and Instrument Scheme

LUBRICANT

The lubricant used for this program was a polyester oil which conforms to MIL-L-23699-A. The lubricant has been used extensively in rig and engine testing at P&WA, and in the field service operation of P&WA engines. It was used, also, for testing of the eight bearings under Contract NAS3-13491. The characteristics of this lubricant are presented in Table I.

TABLE I
LUBRICANT CHARACTERISTICS

Kinematic Viscosity:		
At 233.2°K; - 40°F	1.3×10^{-2} meter^2/sec (Max.);	13,000 Centistokes (Max.)
310.9°K; 100°F	1.0×10^{-4} meter^2/sec (Max.);	100 Centistokes (Max.)
372.0°K; 210°F	5.5×10^{-6} meter^2/sec (Max.);	5.5 Centistokes (Max.)
477.6°K; 400°F	1.0×10^{-6} meter^2/sec (Max.);	1.0 Centistokes (Max.)
Flash Point:	477.6°K; 400°F (Min)	
Evaporation Loss After 6½ Hours:		
At Sea Level, 477.6°K; 400°F	25% (Max.)	
12,192 meters, 477.6°K; 40,000 ft, 400°F	50% (Max.)	
Gear Scuffing Load:	420.3 newtons/mm; 2400 lb/in. (Min.)	
Pitting Fatigue	100 hours (Min.)	
Change From Original Viscosity at 310.9°K; 100°F: (After 72 Hours at 448.2°K; 347°F)	-5 to +15%	
Change From Original Total Acid Number: (After 72 Hours at 448.2°K; 347°F)	2.0 (Max.)	
Quality:	Lubricant free of suspended matter, grit water, and objectionable odor.	

TEST MEASUREMENTS

The parameters measured during the test program and the accuracies attained are listed in Table II.

TABLE II
TEST MEASUREMENTS

Thrust Load	**0.5% of full-scale gage reading**
Shaft Speed	**0.5% of measured speed**
Oil-Flow Rate	**1.0% of full-scale meter reading**
Oil-in Temperature	**±1.1°K up to 549.8°K; ±2°F up to 530°F**
Oil-out Temperature	**±1.1°K up to 549.8°K; ±2°F up to 530°F**
Outer Race Temperature	**±1.1°K up to 549.8°K; ±2°F up to 530°F**
Bearing Cage Speed	**±0.2% of measured speed**
Rig Vibration	**2.0% of full-scale meter reading**

All pertinent rig and bearing temperatures were recorded on a multichannel, 255.4 - 588.7°K (0-600°F), Alumel-Chromel, Bristol Flight Recorder which provided a permanent record with a complete set of temperature data taken every 15 seconds.

Alumel-Chromel thermocouples were immersed in the lubrication system to monitor rig oil-in and oil-out temperatures. Four equally-spaced Alumel-Chromel thermocouples were tack-welded to each outer race OD surface to measure bearing temperatures as illustrated in Figure 13.

THERMAL STABILITY CRITERIA

A supplementary thermocouple circuit, shown in Figure 14, was utilized to determine bearing thermal stability at constant operating conditions after a test point was set. Thermal stability was assumed to exist when the difference between outer-race temperature and oil-in temperature did not change by more than 1.1°K (2°F) in a period of five minutes. This approach was used because changes in oil-in temperature are reflected quickly in corresponding changes in outer-race temperature. Both temperatures can change slightly over a period of minutes as a result of practical limitations of the oil temperature control system, even though bearing heat generation has stabilized. Stabilization of the differential temperature measurement provided a direct indication that bearing heat generation had stabilized.

Since the test rig imposed substantially identical operating conditions on both test bearings simultaneously, the supplementary circuit was attached only to the front bearing during each test sequence. Variation in the differential temperature was easily interpreted to within 0.06°K (0.10°F) on a Bristol 760 Recorder. A typical stabilization chart for a five minute period is shown in Figure 15. The absolute difference between outer-race and oil-in temperature for the bearing in the rear rig position was recorded in millivolts on the same Bristol 760 Recorder.

BEARING CAGE SPEED

A special technique developed at Pratt & Whitney Aircraft was used to measure the bearing cage speed without affecting bearing operation. The measurement was made with a micro-measurement DGP-1000-500 semi-conductor strain gage attached to the bearing outer-race (Figure 13). The gage senses the change in outer-race strain as each ball passes the gage site, and produces signals at a rate proportional to cage speed and the number of balls in the bearing. The measurements are very accurate and provided a means for detecting ball skidding.

RIG VIBRATION

Rig vibration was monitored by bearing failure indicators developed by Pratt & Whitney Aircraft to detect abnormal bearing operating conditions. With this sensitive instrumentation, an increase of vibration would have indicated ball or race spalling at its inception, making it possible to terminate the test before gross damage occurred. This is an important aid in any failure analysis, and minimizes the possibility of rig damage and wasted test effort.

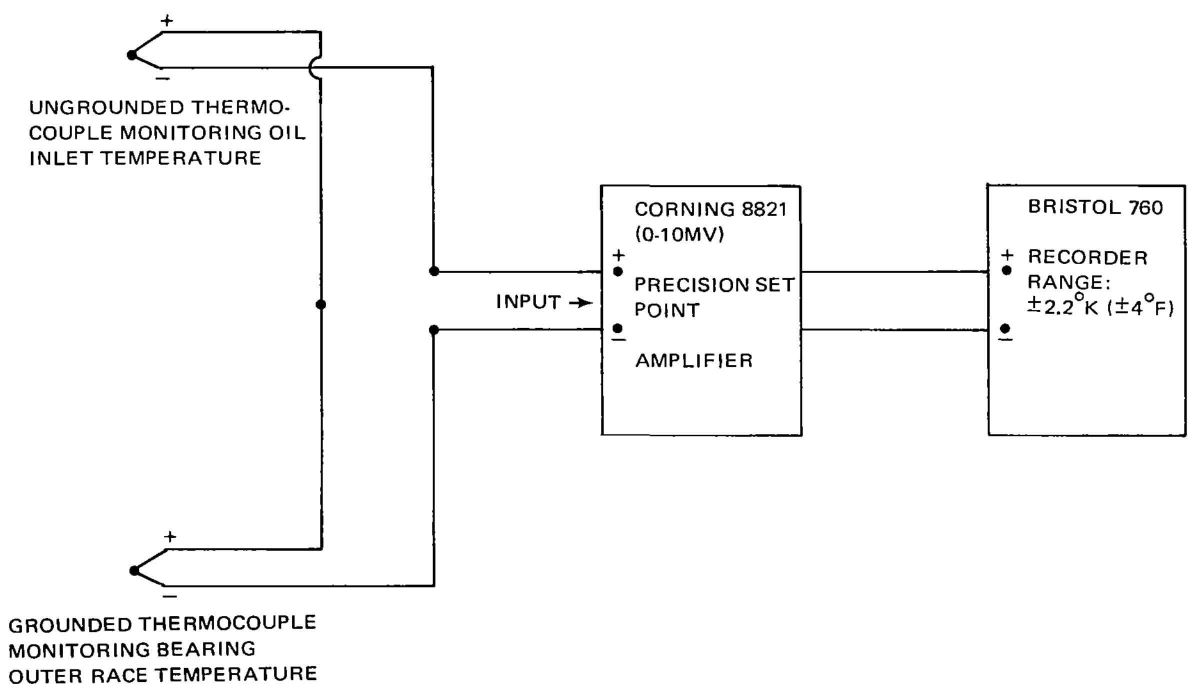


Figure 14 Supplementary Thermocouple Circuit

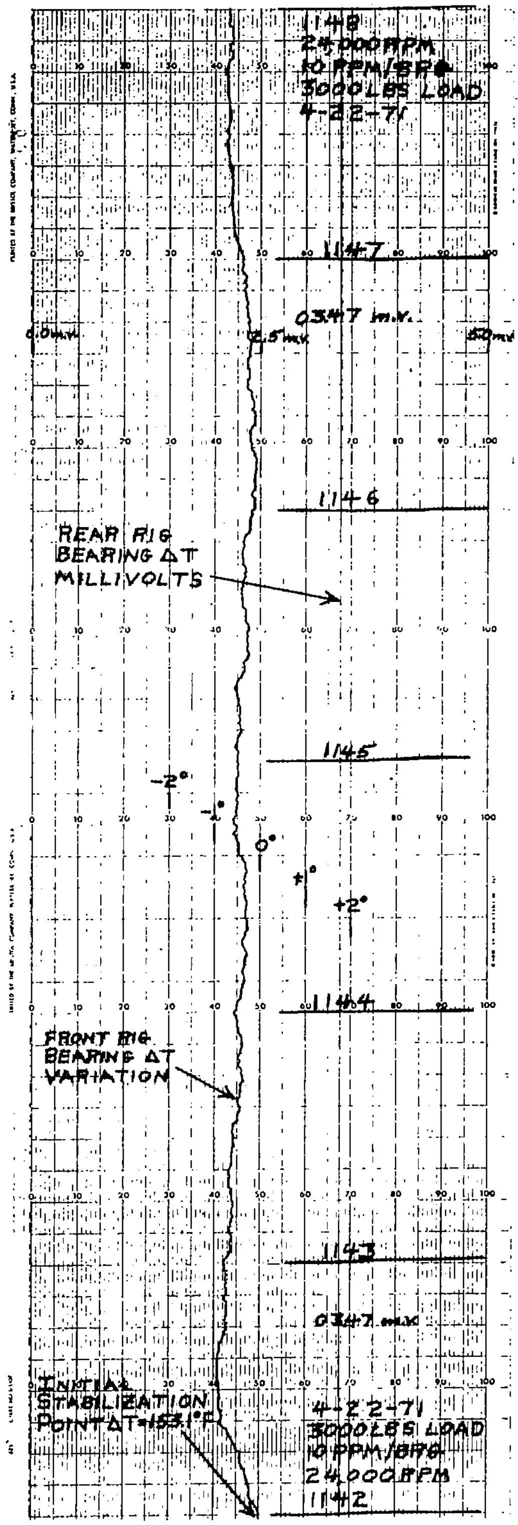


Figure 15 Typical ΔT Stabilization Chart

TASK III SKID-MAPPING TESTS

During Task II of this contract, tests were conducted to compare the performance of drilled-ball bearings at various oil flow rates with that of equivalent solid-ball bearings. The tests were performed over a wide range of DN values and over an oil flow range broad enough to define the "optimum" oil flow rate at which bearing temperatures were minimized. The thrust load was maintained at a value which ensured that destructive skidding would be avoided at all test speeds and oil flow rates. These tests were covered in the First Topical Report (PWA-4235). Task III was undertaken to compare the skid behavior of drilled-ball bearings with that of equivalent solid-ball bearings at the bearing's optimum oil flow rate up to 3.0 million DN.

The general approach utilized in this task for documenting bearing skid behavior at any specific DN value was to establish an initial thrust load that was high enough to ensure proper bearing operation and then observe the changes in bearing cage speed as load was reduced incrementally. Bearing cage speed tends to decrease relative to shaft speed when ball skidding occurs which provides a convenient and sensitive skidding indicator for experimental purposes. A bearing lubricant supply of 121×10^{-3} kilograms per second (16 lb/min) was selected as the optimum flow on the basis of the Task II test results. The tests were conducted at two different oil supply temperatures, 366.5°F (200°F) and 388.7°K (240°F), because work in other programs had shown that skid behavior could change markedly with rather modest changes in oil supply temperatures.

TEST CONDITIONS

The basic test plan was to operate both solid and drilled-ball bearings at the conditions given in Table III.

TABLE III

SKID MAPPING TESTS – OPERATING CONDITIONS

Temperature:	Oil in 366.5°K ± 1.7°K; 200°F ± 3°F 388.7°K ± 1.7°K; 240°F ± 3°F	
Oil Flow Rate:	121×10^{-3} kg/sec (16 lb/min)/bearing	
Speed:	1.0×10^6 DN	(8,000 rpm)
	1.5×10^6 DN	(12,000 rpm)
	2.0×10^6 DN	(16,000 rpm)
	2.4×10^6 DN	(19,200 rpm)
	2.8×10^6 DN	(22,400 rpm)
	3.0×10^6 DN	(24,000 rpm)
Thrust Load:	Initially 22,241 newtons (5000 lb) per bearing diminishing incrementally to a minimum load which is one-half of the thrust load for which maximum cage speed is obtained or the load below which an undesirably large decrease in cage speed is observed.	

Both bearing configurations were to be tested initially at an oil supply nominal temperature of 366.5°K (200°F). This temperature had been used in the previous bearing tests to date and approximates the oil supply temperature expected in normal engine operation. Subsequent tests were to be conducted at a higher oil supply nominal temperature of 388.7°K (240°F) to determine if bearing skid behavior would change markedly. A maximum bearing outer-ring temperature was established at 491.5°K (425°F) to prevent damage from excessive temperature. Bearing lubricant was to be supplied at the optimum flow of 121 x 10^{-3} kilograms per second (16 lb/min) at each DN value to provide ample lubrication and to minimize operating temperatures. However, the bearing oil supply at 1.0 million DN was restricted to approximately 95 X 10^{-3} kilograms per second (12.5 lb/min) because of decreased scoop efficiency discovered during Task I testing. The maximum bearing thrust load was reduced from 22,241 newtons (5000 lb) to 13,344 newtons (3000 lb) for drilled-ball bearing tests at 388.7°K (240°F) oil supply temperature after a drilled-ball bearing failed during skid tests at 366.5°K (200°F) oil supply temperature.

TEST PROCEDURE

Testing was started at each oil supply temperature with two solid-ball bearings and then repeated with two drilled-ball bearings to obtain comparative data. The startup-shutdown procedure shown in Table IV, originally developed under Contract NAS3-13491, was used for all tests during Task III.

TABLE IV

STARTUP-SHUTDOWN PROCEDURES FOR SOLID-BALL AND DRILLED-BALL BEARINGS

STARTUP

1. Set rig shaft speed at 1000 rpm
2. Increase bearing thrust load to 1,112-1,668 newtons (250-375 lb)
3. Increase rig speed to 6000 rpm
4. Increase thrust load to 4,448 newtons (1000 lb)
5. Increase rig speed to 8000 rpm
6. Increase thrust load to maximum value
7. Increase rig speed to test condition

TABLE IV (Cont'd)

SHUTDOWN

1. Decrease rig shaft speed to 8000 rpm
2. Decrease bearing thrust load to 4,448 newtons (1000 lb)
3. Decrease rig speed to 6000 rpm
4. Decrease thrust load to 2,224 newtons (500 lb)
5. Decrease rig speed to 4000 rpm
6. Decrease thrust load to 1,112-1,668 newtons (250-375 lb)
7. Decrease rig speed to 1000 rpm
8. Decrease rig speed and thrust load simultaneously to zero

Each test series, at a specific oil supply temperature, was initiated at 1.0 million DN and progressed to successively higher DN values. At each DN value, the maximum bearing thrust load was set and operating conditions were maintained constant while thermal equilibrium was established. Thermal equilibrium was assumed to exist when the difference between outer-race temperature and oil-in temperature did not change by more than 1.1°K (2°F) in a period of five minutes. After thermal equilibrium was established and test measurements recorded, bearing thrust load was reduced in successive steps to a minimum thrust load afterwhich thrust load was returned to its maximum value to complete the load cycle. Testing at each combination of DN value and thrust load was continued for a sufficiently long period of time to make test measurements and record data but did not exceed thirty minutes at the maximum thrust load condition at each DN value or fifteen minutes at each of the other thrust load settings. Testing at any combination of DN value and thrust load was to be abandoned if the bearing outer-ring temperature exceeded 491.5°K (425°F). Testing of any bearing pair was to be terminated if a bearing failure occurred at any test condition.

Work in other programs had shown that the maximum cage speed of a ball bearing usually occurs at a different thrust load for each DN level. Initially, load settings in each Task III thrust-load reduction cycle were selected to determine the maximum cage speed at each DN level and consequently the minimum thrust load for each cycle, as defined in Table III.

It became evident early in the solid-ball tests and later in the drilled-ball tests that the maximum cage speed value for each DN level occurred at approximately the maximum bearing thrust load setting. On the basis of the thrust load criterion in Table III, the minimum thrust load in each thrust-load reduction cycle would be approximately 6,672 newtons (1500 lb) to 8,896 newtons (2000 lb). It was also apparent that the amount of cage speed reduction was not as large as anticipated even at these lower thrust loads. Consequently, the

thrust-load reduction cycle for each DN level was extended to provide more frequent settings between 22,241 newtons (5000 lb) and approximately 1,668 newtons (375 lb). The lowest load was limited to 1,668 newtons (375 lb) because of limitations within the stand loading system. The thrust-load reduction cycles finally used at each DN level for the solid-ball and drilled-ball tests are presented in the Task III data summary tables.

SOLID-BALL BEARING TESTS

Two solid-ball bearings (S/N 2560A-1 and S/N 2560 A-2) successfully completed skid-mapping tests up to 3.0 million DN (24,000 rpm) at 366.5°K (200°F) oil supply temperature. One thrust-load reduction cycle was run at each DN level up to 2.8 million DN. Three cycles were run at 3.0 million DN because the oil supply temperature ranged between 369.8°K (206°F) and 374.8°K (215°F) during the first cycle. Subsequently, the same bearings successfully completed tests up to 3.0 million DN at 388.7°K (240°F) oil supply temperature. Only one thrust-load reduction cycle was run at each DN level in this test series. Bearing thrust loads generally ranged from 22,241 newtons (5000 lb) to approximately 1,779 newtons (400 lb) in each load reduction cycle conducted at all DN levels and both oil supply temperatures.

Solid-Ball Bearing Performance

Cage speed and temperature data for the two solid-ball bearings (S/N 2560 A-1 and S/N 2560 A-2) are summarized in Tables V through XVIII. Tables V through XII provide the data for the skid-mapping test series at an oil supply temperature of 366.5°K (200°F), and Tables XIII through XVIII provide the data for the test series at 388.7°K (240°F) oil supply temperature.

Skid-Mapping Tests at 366.5°K Oil Supply Temperature

At the 366.5°K (200°F) oil supply temperature, bearing cage speeds did not change significantly during the thrust-load reduction cycles at speeds through 2.4 million DN. However, at 2.8 million DN and 3.0 million DN cage speeds did change significantly and were accompanied by larger changes in differential temperatures than occurred at the lower DN values.

The one test at 2.8 million DN is summarized in Tables IX and X. Cage speed reductions of 1.08 and 1.72 percent of shaft speed occurred for the front and rear bearings over the entire thrust-load reduction cycle. Bearing cage speeds decreased gradually with decreases in load from 22,241 newtons (5000 lb) to 2,802 newtons (630 lb). The biggest change of 0.46 percent for both bearings occurred during the small load-change from 2,802 newtons (630 lb) to 2,335 newtons (525 lb). Simultaneously, the largest decrease in bearing differential-temperatures and oil outlet temperatures occurred at this time and was accompanied by a quite noticeable change in the noise generated within the test rig. The pitch of the noise emission became much higher, becoming extremely shrill, and continued as thrust load was reduced further to the minimum value of 1,401 newtons (315 lb). During this time there was no significant change in rig vibration. The shrill noise did not cease until after the bearing thrust load was increased above 13,344 newtons (3000 lb).

TABLE V
TASK III SKID STUDY
SOLID-BALL BEARING
366.5°K OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN52575 S/N 2560A-2					NO. 1 BEARING (FRONT) P/N SKN52575 S/N 2560A-1						
(1) Thrust Load (newtons)	(2) DN x 10^6	(3) Shaft Speed (rpm)	(4) Cage Speed Percent*	(5) Oil Inlet Temp (°K)	(6) Avg. Outer Race Temp (°K)	(7) Outer Race Oil Inlet ΔT (°K)	(8) Avg. Oil Outlet Temp (°K)	(9) Cage Speed Percent*	(10) Oil Inlet Temp (°K)	(11) Avg. Outer Race Temp (°K)	(12) Outer Race Oil Inlet ΔT (°K)	(13) Avg. Oil Outlet Temp (°K)	(14) Outer Race - Oil Inlet Measured ΔT** (°K) Variation For a 5 Minute Time Period	(15)
22241	1.0	8,000	44.54	366.48	389.26	22.78	384.82	44.50	366.48	389.26	22.78	384.82	20.72-21.27	(0.55)
17793	1.0	8,000	44.79	365.93	388.15	22.22	383.71	44.75	365.93	388.15	22.22	383.71	–	–
13344	1.0	8,000	44.86	365.93	387.59	21.66	383.71	44.86	365.93	387.59	21.66	383.71	–	–
11121	1.0	81000	44.64	365.93	387.59	21.66	383.15	44.64	365.93	387.59	21.66	383.15	–	–
8896	1.0	8,000	44.61	365.93	387.59	21.66	383.15	44.61	365.93	387.59	21.66	383.15	–	–
7784	1.0	8,000	44.71	365.93	387.59	21.66	383.15	44.68	365.93	387.59	21.66	383.15	–	–
6672	1.0	8,000	44.79	366.48	388.15	21.67	383.71	44.71	366.48	388.15	21.67	383.71	–	–
5560	1.0	8,000	44.86	367.04	388.15	21.11	383.71	44.82	367.04	388.15	21.11	383.71	–	–
4448	1.0	8,000	44.86	366.48	388.15	21.67	383.71	44.86	366.48	387.59	21.11	383.71	–	–
3972	1.0	8,000	44.86	367.04	387.59	20.55	383.71	44.82	367.04	387.59	20.55	383.71	–	–
3736	1.0	8,000	44.96	366.48	387.59	21.11	383.71	44.93	366.48	387.59	21.11	383.71	–	–
3500	1.0	8,000	45.00	366.48	387.59	21.11	383.71	44.96	366.48	387.59	21.11	383.71	–	–
3269	1.0	8,000	44.71	366.48	387.59	21.11	383.71	44.68	366.48	387.59	21.11	383.71	–	–
3034	1.0	8,000	44.75	367.04	387.59	20.55	383.71	44.71	367.04	387.59	20.55	383.71	–	–
2802	1.0	8,000	44.82	367.04	387.59	20.55	383.71	44.79	367.04	387.59	20.55	383.71	–	–
2571	1.0	8,000	44.86	367.04	387.59	20.55	383.71	44.79	367.04	387.59	20.55	383.71	–	–
2335	1.0	8,000	44.86	367.04	387.59	20.55	383.71	44.82	367.04	387.59	20.55	383.71	–	–
2104	1.0	8,000	44.93	367.04	387.59	20.55	383.71	44.86	367.04	387.59	20.55	383.71	–	–
1868	1.0	8,000	44.96	367.04	387.59	20.55	383.15	44.89	367.04	387.59	20.55	383.15	–	–
1636	1.0	8,000	45.00	367.04	387.59	20.55	383.71	44.93	367.04	387.59	20.55	383.15	–	–
1401	1.0	8,000	45.00	367.04	387.59	20.55	383.71	44.93	367.04	387.59	20.55	383.15	–	–
22241	1.5	12,000	45.86	367.59	404.26	36.67	398.15	45.64	367.59	401.48	33.89	395.37	32.22-32.55	(0.33)
17793	1.5	12,000	45.79	367.59	402.04	34.45	397.04	45.57	367.59	400.37	32.78	395.37	–	–
13344	1.5	12,000	45.67	367.59	402.04	34.45	396.48	45.45	367.59	400.37	32.78	395.37	–	–
11121	1.5	12,000	45.76	367.59	402.04	34.45	396.48	45.55	367.59	399.82	32.23	395.37	–	–
8896	1.5	12,000	45.67	367.59	401.48	33.89	396.48	45.45	367.59	399.82	32.23	395.37	–	–
7784	1.5	12,000	45.81	367.59	401.48	33.89	395.93	45.57	367.59	399.82	32.23	395.37	–	–
6672	1.5	12,000	45.71	367.59	401.48	33.89	396.48	45.48	367.59	399.82	32.23	395.37	–	–
5560	1.5	12,000	45.67	367.04	401.48	34.44	395.93	45.40	367.04	399.82	32.78	395.37	–	–
4893	1.5	12,000	45.60	367.04	400.93	33.89	395.93	45.33	367.04	399.26	32.22	395.37	–	–
4448	1.5	12,000	45.74	367.59	401.48	33.89	395.93	45.48	367.59	399.26	31.67	395.37	–	–
4204	1.5	12,000	45.67	367.59	400.93	33.34	395.93	45.43	367.59	399.26	31.67	394.82	–	–
3972	1.5	12,000	45.74	367.04	400.93	33.89	395.93	45.48	367.04	398.71	31.67	394.82	–	–
3736	1.5	12,000	45.76	367.04	400.37	33.33	395.37	45.48	367.04	398.71	31.67	394.26	–	–
3500	1.5	12,000	45.71	367.04	400.37	33.33	395.37	45.43	367.04	398.71	31.67	394.82	–	–
3269	1.5	12,000	45.67	367.04	400.37	33.33	395.37	45.38	367.04	398.71	31.67	394.26	–	–
3034	1.5	12,000	45.76	367.59	400.37	32.78	395.93	45.48	367.59	398.71	31.12	394.82	–	–
2802	1.5	12,000	45.69	367.59	400.37	32.78	395.93	45.40	367.59	398.71	31.12	394.82	–	–
2571	1.5	12,000	45.64	367.59	400.37	32.78	395.93	45.36	367.59	398.71	31.12	394.26	–	–
2335	1.5	12,000	45.76	367.59	400.37	32.78	395.93	45.50	367.59	398.71	31.12	394.82	–	–
2104	1.5	12,000	45.64	367.04	400.37	33.33	395.37	45.38	367.04	398.15	31.11	394.82	–	–
1868	1.5	12,000	45.83	367.04	400.37	33.33	395.37	45.55	367.04	398.15	31.11	394.26	–	–
1636	1.5	12,000	45.64	367.04	399.82	32.78	395.37	45.38	367.04	398.15	31.11	394.26	–	–
1401	1.5	12,000	45.62	367.59	399.26	31.67	394.82	45.33	367.59	398.15	30.56	394.26	–	–

* Cage speed is expressed as percent of shaft rpm.

** Bearing outer-race oil inlet ΔT is measured directly by a supplementary circuit for determining thermal stability.

TABLE VI
TASK III SKID STUDY
SOLID-BALL BEARING
200°F OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN52575 S/N 2560A-2					NO. 1 BEARING (FRONT) P/N SKN52575 S/N 2560A-1						
(1) Thrust Load (lb)	(2) DN x 10^6	(3) Shaft Speed (rpm)	(4) Cage Speed Percent*	(5) Oil Inlet Temp (°F)	(6) Avg. Outer Race Temp (°F)	(7) Outer Race Oil Inlet ΔT (°F)	(8) Avg. Oil Outlet Temp (°F)	(9) Cage Speed Percent*	(10) Oil Inlet Temp (°F)	(11) Avg. Outer Race Temp (°F)	(12) Outer Race Oil Inlet ΔT (°F)	(13) Avg. Oil Outlet Temp (°F)	(14) Outer Race - Oil Inlet Measured ΔT** (°F)	(15) Variation For a 5 Minute Time Period
5000	1.0	8,000	44.54	200	241	41	233	44.50	200	241	41	233	37.3 - 38.3	(1.0)
4000	1.0	8,000	44.79	199	239	40	231	44.75	199	239	40	231	–	–
3000	1.0	8,000	44.86	199	238	39	231	44.86	199	238	39	231	–	–
2500	1.0	8,000	44.64	199	238	39	230	44.64	199	238	39	230	–	–
2000	1.0	8,000	44.61	199	238	39	230	44.61	199	238	39	230	–	–
1750	1.0	8,000	44.71	199	238	39	230	44.68	199	238	39	230	–	–
1500	1.0	8,000	44.79	200	239	39	231	44.71	200	239	39	231	–	–
1250	1.0	8,000	44.86	201	239	38	231	44.82	201	239	38	231	–	–
1000	1.0	8,000	44.86	200	239	39	231	44.86	200	238	38	231	–	–
893	1.0	8,000	44.86	201	238	37	231	44.82	201	238	37	231	–	–
840	1.0	8,000	44.96	200	238	38	231	44.93	200	238	38	231	–	–
787	1.0	8,000	45.00	200	238	38	231	44.96	200	238	38	231	–	–
735	1.0	8,000	44.71	200	238	38	231	44.68	200	238	38	231	–	–
682	1.0	8,000	44.75	201	238	37	231	44.71	201	238	37	231	–	–
630	1.0	8,000	44.82	201	238	37	231	44.79	201	238	37	231	–	–
578	1.0	8,000	44.86	201	238	37	231	44.79	201	238	37	231	–	–
525	1.0	8,000	44.86	201	238	37	231	44.82	201	238	37	231	–	–
473	1.0	8,000	44.93	201	238	37	231	44.86	201	238	37	231	–	–
420	1.0	8,000	44.96	201	238	37	230	44.89	201	238	37	230	–	–
368	1.0	8,000	45.00	201	238	37	231	44.93	201	238	37	230	–	–
315	1.0	8,000	45.00	201	238	37	231	44.93	201	238	37	230	–	–
5000	1.5	12,000	45.86	202	268	66	257	45.64	202	263	61	252	58.0 - 58.6	(0.6)
4000	1.5	12,000	45.79	202	264	62	255	45.57	202	261	59	252	–	–
3000	1.5	12,000	45.67	202	264	62	254	45.45	202	261	59	252	–	–
2500	1.5	12,000	45.76	202	264	62	254	45.55	202	260	58	252	–	–
2000	1.5	12,000	45.67	202	263	61	254	45.45	202	260	58	252	–	–
1750	1.5	12,000	45.81	202	263	61	253	45.57	202	260	58	252	–	–
1500	1.5	12,000	45.71	202	263	61	254	45.48	202	260	58	252	–	–
1250	1.5	12,000	45.67	201	263	62	253	45.40	201	260	59	252	–	–
1100	1.5	12,000	45.60	201	262	61	253	45.33	201	259	58	252	–	–
1000	1.5	12,000	45.74	202	263	61	253	45.48	202	259	57	252	–	–
945	1.5	12,000	45.67	202	262	60	253	45.43	202	259	57	251	–	–
893	1.5	12,000	45.74	201	262	61	253	45.48	201	258	57	251	–	–
840	1.5	12,000	45.76	201	261	60	252	45.48	201	258	57	250	–	–
787	1.5	12,000	45.71	201	261	60	252	45.43	201	258	57	251	–	–
735	1.5	12,000	45.67	201	261	60	252	45.38	201	258	57	250	–	–
682	1.5	12,000	45.76	202	261	59	253	45.48	202	258	56	251	–	–
630	1.5	12,000	45.69	202	261	59	253	45.40	202	258	56	251	–	–
578	1.5	12,000	45.64	202	261	59	253	45.36	202	258	56	250	–	–
525	1.5	12,000	45.76	202	261	59	253	45.50	202	258	56	251	–	–
473	1.5	12,000	45.64	201	261	60	252	45.38	201	257	56	251	–	–
420	1.5	12,000	45.83	201	261	60	252	45.55	201	257	56	250	–	–
368	1.5	12,000	45.64	201	260	59	252	45.38	201	257	56	250	–	–
315	1.5	12,000	45.62	202	259	57	251	45.33	202	257	55	250	–	–

* Cage speed is expressed as percent of shaft rpm.

** Bearing outer-race oil inlet ΔT is measured directly by a supplementary circuit for determining thermal stability.

TABLE VII
TASK III SKID STUDY
SOLID-BALL BEARING
366.5°K OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN52575 S/N 2560A-2					NO. 1 BEARING (FRONT) P/N SKN52575 S/N 2560A-1						
(1) Thrust Load (newtons)	(2) DN x 10^6	(3) Shaft Speed (rpm)	(4) Cage Speed Percent*	(5) Oil Inlet Temp (°K)	(6) Avg. Outer Race Temp (°K)	(7) Outer Race Oil Inlet ΔT (°K)	(8) Avg. Oil Outlet Temp (°K)	(9) Cage Speed Percent*	(10) Oil Inlet Temp (°K)	(11) Avg. Outer Race Temp (°K)	(12) Outer Race Oil Inlet ΔT (°K)	(13) Avg. Oil Outlet Temp (°K)	(14) Outer Race - Oil Inlet Measured ΔT** (°K)	(15) Variation For a 5 Minute Time Period
22241	2.0	16,000	45.96	368.15	417.04	48.89	410.93	45.45	368.15	414.82	46.67	411.48	45.94-46.16	(0.22)
17793	2.0	16,000	45.82	368.15	417.04	48.89	411.48	45.32	368.15	414.82	46.67	411.48	–	–
13344	2.0	16,000	45.79	368.15	415.93	47.78	410.93	45.29	368.15	414.26	46.11	410.93	–	–
11121	2.0	16,000	45.71	367.04	415.93	48.89	409.26	45.21	367.04	414.26	47.22	409.82	–	–
10008	2.0	16,000	45.77	368.15	415.93	47.78	409.82	45.29	368.15	413.71	45.56	410.37	–	–
8896	2.0	16,000	45.70	368.15	415.93	47.78	409.82	45.20	368.15	413.71	45.56	410.93	–	–
7784	2.0	16,000	45.79	368.15	415.37	47.22	410.37	45.30	368.15	413.71	45.56	410.93	–	–
6672	2.0	16,000	45.79	368.15	415.37	47.22	409.82	45.27	368.15	413.71	45.56	410.37	–	–
5560	2.0	16,000	45.70	367.04	414.26	47.22	409.26	45.20	367.04	412.59	45.55	409.26	–	–
4893	2.0	16,000	45.64	366.48	413.71	47.23	408.71	45.16	366.48	412.04	45.56	409.26	–	–
4448	2.0	16,000	45.61	366.48	413.71	47.23	408.15	45.11	366.48	412.04	45.56	408.71	–	–
4204	2.0	16,000	45.68	365.93	413.15	47.22	408.15	45.20	365.93	411.48	45.55	408.71	–	–
3736	2.0	16,000	45.64	365.93	413.71	47.78	408.71	45.16	365.93	412.04	46.11	408.71	–	–
3269	2.0	16,000	45.70	366.48	413.71	47.23	408.71	45.21	366.48	412.04	45.56	408.71	–	–
2802	2.0	16,000	45.62	366.48	413.71	47.23	408.71	45.14	366.48	412.04	45.56	408.71	–	–
2335	2.0	16,000	45.68	366.48	413.71	47.23	408.71	45.21	366.48	412.04	45.56	408.71	–	–
1868	2.0	16,000	45.75	366.48	413.71	47.23	408.71	45.25	366.48	412.04	45.56	408.71	–	–
1636	2.0	16,000	45.64	366.48	413.71	47.23	408.71	45.14	366.48	412.04	45.56	408.71	–	–
1401	2.0	16,000	45.64	366.48	413.71	47.23	408.71	45.14	366.48	412.04	45.56	408.71	–	–
22241	2.4	19,200	45.58	367.04	427.59	60.55	421.48	45.15	367.04	425.37	58.33	422.04	57.44-57.94	(0.50)
17792	2.4	19,200	45.39	367.04	426.48	59.44	420.37	45.04	367.04	425.37	58.33	422.04	–	–
15569	2.4	19,200	45.42	367.04	426.48	59.44	420.37	45.06	367.04	425.37	58.33	421.48	–	–
13345	2.4	19,200	45.34	367.04	426.48	59.44	420.37	45.01	367.04	424.82	57.78	421.48	–	–
11121	2.4	19,200	45.31	367.04	426.48	59.44	420.37	44.97	367.04	424.82	57.78	421.48	–	–
8896	2.4	19,200	45.31	367.04	425.93	58.89	420.37	44.99	367.04	424.82	57.78	421.48	–	–
7784	2.4	19,200	45.30	367.04	425.37	58.33	419.82	44.99	367.04	424.26	57.22	420.93	–	–
6672	2.4	19,200	45.22	367.04	425.37	58.33	419.82	44.93	367.04	424.26	57.22	420.93	–	–
5560	2.4	19,200	45.22	367.04	425.37	58.33	419.82	44.93	367.04	424.26	57.22	420.93	–	–
4893	2.4	19,200	45.25	367.04	425.37	58.33	420.37	44.97	367.04	424.26	57.22	420.93	–	–
4448	2.4	19,200	45.12	367.04	425.37	58.33	419.82	44.82	367.04	424.26	57.22	420.93	–	–
4204	2.4	19,200	45.13	367.04	425.37	58.33	419.82	44.87	367.04	424.26	57.22	420.93	–	–
3736	2.4	19,200	45.15	367.04	425.37	58.33	419.82	44.85	367.04	424.26	57.22	420.93	–	–
3269	2.4	19,200	45.18	367.04	425.37	58.33	419.82	44.88	367.04	424.26	57.22	420.93	–	–
2802	2.4	19,200	45.13	367.04	425.37	58.33	419.82	44.85	367.04	424.26	57.22	420.93	–	–
2335	2.4	19,200	45.13	367.04	425.37	58.33	418.15	44.87	367.04	424.26	57.22	420.93	–	–
1868	2.4	19,200	45.16	367.04	425.37	58.33	419.82	44.88	367.04	424.26	57.22	420.93	–	–
1636	2.4	19,200	45.13	367.04	425.37	58.33	419.82	44.88	367.04	424.26	57.22	420.93	–	–
1401	2.4	19,200	45.13	367.04	425.37	58.33	419.82	44.87	367.04	424.26	57.22	420.93	–	–

* Cage speed expressed as a percent of shaft rpm.

** Bearing outer-race oil inlet ΔT is measured directly by a supplementary circuit for determining thermal stability.

TABLE VIII
TASK III SKID STUDY
SOLID-BALL BEARING
200°F OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN52575 S/N 2560A-2					NO. 1 BEARING (FRONT) P/N SKN52575 S/N 2560A-1						
(1) Thrust Load (lb)	(2) DN x 10^6	(3) Shaft Speed (rpm)	(4) Cage Speed Percent*	(5) Oil Inlet Temp (°F)	(6) Avg. Outer Race Temp (°F)	(7) Outer Race Oil Inlet ΔT (°F)	(8) Avg. Oil Outlet Temp (°F)	(9) Cage Speed Percent*	(10) Oil Inlet Temp (°F)	(11) Avg. Outer Race Temp (°F)	(12) Outer Race Oil Inlet ΔT (°F)	(13) Avg. Oil Outlet Temp (°F)	(14) Outer Race - Oil Inlet Measured ΔT** (°F)	(15) Variation For a 5 Minute Time Period
5000	2.0	16,000	45.96	203	291	88	280	45.45	203	287	84	281	82.7 - 83.1	(0.4)
4000	2.0	16,000	45.82	203	291	88	281	45.32	203	287	84	281	–	–
3000	2.0	16,000	45.79	203	289	86	280	45.29	203	286	83	280	–	–
2500	2.0	16,000	45.71	201	289	88	277	45.21	201	286	85	278	–	–
2250	2.0	16,000	45.77	203	289	86	278	45.29	203	285	82	279	–	–
2000	2.0	16,000	45.70	203	289	86	278	45.20	203	285	82	280	–	–
1750	2.0	16,000	45.79	203	288	85	279	45.30	203	285	82	280	–	–
1500	2.0	16,000	45.79	203	288	85	278	45.27	203	285	82	279	–	–
1250	2.0	16,000	45.70	201	286	85	277	45.20	201	283	82	277	–	–
1100	2.0	16,000	45.64	200	285	85	276	45.16	200	282	82	277	–	–
1000	2.0	16,000	45.61	200	285	85	275	45.11	200	282	82	276	–	–
945	2.0	16,000	45.68	199	284	85	275	45.20	199	281	82	276	–	–
840	2.0	16,000	45.64	199	285	86	276	45.16	199	282	83	276	–	–
735	2.0	16,000	45.70	200	285	85	276	45.21	200	282	82	276	–	–
630	2.0	16,000	45.62	200	285	85	276	45.14	200	282	82	276	–	–
525	2.0	16,000	45.68	200	285	85	276	45.21	200	282	82	276	–	–
420	2.0	16,000	45.75	200	285	85	276	45.25	200	282	82	276	–	–
368	2.0	16,000	45.64	200	285	85	276	45.14	200	282	82	276	–	–
315	2.0	16,000	45.64	200	285	85	276	45.14	200	282	82	276	–	–
5000	2.4	19,200	45.58	201	310	109	299	45.15	201	306	105	300	103.4 - 104.3	(0.9)
4000	2.4	19,200	45.39	201	308	107	297	45.04	201	306	105	300	–	–
3500	2.4	19,200	45.42	201	308	107	297	45.06	201	306	105	299	–	–
3000	2.4	19,200	45.34	201	308	107	297	45.01	201	305	104	299	–	–
2500	2.4	19,200	45.31	201	308	107	297	44.97	201	305	104	299	–	–
2000	2.4	19,200	45.31	201	307	106	297	44.99	201	305	104	299	–	–
1750	2.4	19,200	45.30	201	306	105	296	44.99	201	304	103	298	–	–
1500	2.4	19,200	45.22	201	306	105	296	44.93	201	304	103	298	–	–
1250	2.4	19,200	45.22	201	306	105	296	44.93	201	304	103	298	–	–
1100	2.4	19,200	45.25	201	306	105	297	44.97	201	304	103	298	–	–
1000	2.4	19,200	45.12	201	306	105	296	44.82	201	304	103	298	–	–
945	2.4	19,200	45.13	201	306	105	296	44.87	201	304	103	298	–	–
840	2.4	19,200	45.15	201	306	105	296	44.85	201	304	103	298	–	–
735	2.4	19,200	45.18	201	306	105	296	44.88	201	304	103	298	–	–
630	2.4	19,200	45.13	201	306	105	296	44.85	201	304	103	298	–	–
525	2.4	19,200	45.13	201	306	105	293	44.87	201	304	103	298	–	–
420	2.4	19,200	45.16	201	306	105	296	44.88	201	304	103	298	–	–
368	2.4	19,200	45.13	201	306	105	296	44.88	201	304	103	298	–	–
315	2.4	19,200	45.13	201	306	105	296	44.87	201	304	103	298	–	–

* Cage speed is expressed as percent of shaft rpm.

** Bearing outer-race oil inlet ΔT is measured directly by a supplementary circuit for determining thermal stability.

TABLE IX
TASK III SKID STUDY
SOLID-BALL BEARING
366.5°K OIL INLET TEMPERATURE

			NO.2 BEARING (REAR) P/N SKN52575 S/N 2560A-2					NO.1 BEARING (FRONT) P/N SKN52575 S/N 2560A-1						
(1) Thrust Load (newtons)	(2) DN x 10^6	(3) Shaft Speed (rpm)	(4) Cage Speed Percent*	(5) Oil Inlet Temp (°K)	(6) Avg. Outer Race Temp (°K)	(7) Outer Race Oil Inlet ΔT (°K)	(8) Avg. Oil Outlet Temp (°K)	(9) Cage Speed Percent*	(10) Oil Inlet Temp (°K)	(11) Avg. Outer Race Temp (°K)	(12) Outer Race Oil Inlet ΔT (°K)	(13) Avg. Oil Outlet Temp (°K)	(14) Outer Race - Oil Inlet Measured ΔT** (°K) Variation For a 5 Minute Time Period	(15)
22241	2.8	22,400	46.10	368.15	447.59	79.44	440.37	45.47	368.15	443.71	75.56	440.37	75.44-75.55	(0.11)
17793	2.8	22,400	45.96	368.15	448.15	80.00	440.93	45.38	368.15	443.71	75.56	440.37	–	–
15569	2.8	22,400	45.98	368.15	447.59	79.44	440.37	45.37	368.15	443.71	75.56	440.37	–	–
13345	2.8	22,400	45.88	368.15	444.82	76.67	438.71	45.28	368.15	442.04	73.89	438.71	72.78-73.61	(0.83)
11121	2.8	22,400	45.79	368.15	444.26	76.11	438.15	45.28	368.15	441.48	73.33	438.15	–	–
8896	2.8	22,400	45.65	368.15	443.15	75.00	437.59	45.22	368.15	440.37	72.22	437.59	–	–
7784	2.8	22,400	45.60	368.15	443.15	75.00	437.04	45.22	368.15	440.37	72.22	437.04	–	–
6672	2.8	22,400	45.48	367.59	442.04	74.45	437.04	45.22	367.59	439.82	72.23	437.04	–	–
5560	2.8	22,400	45.33	367.59	440.93	73.34	435.37	45.13	367.59	439.26	71.67	435.93	–	–
4893	2.8	22,400	45.08	367.04	439.26	72.22	434.26	45.08	367.04	438.15	71.11	434.82	–	–
4448	2.8	22,400	45.01	367.04	439.26	72.22	433.15	45.01	367.04	437.59	70.55	434.26	71.00-71.11	(0.11)
4204	2.8	22,400	45.00	366.48	438.71	72.23	432.59	45.03	366.48	437.04	70.56	433.71	–	–
3736	2.8	22,400	44.95	366.48	438.15	71.67	432.59	44.95	366.48	437.04	70.56	433.71	–	–
3269	2.8	22,400	44.90	366.48	437.59	71.11	432.04	44.90	366.48	436.48	70.00	433.15	–	–
2802	2.8	22,400	44.85	365.93	437.59	71.66	431.48	44.85	365.93	436.48	70.55	433.15	–	–
2335	2.8	22,400	44.39	365.93	434.82	68.89	428.71	44.39	365.93	434.82	68.89	430.37	–	–
1868	2.8	22,400	44.39	365.37	433.71	68.34	428.15	44.39	365.37	434.26	68.89	429.26	–	–
1637	2.8	22,400	44.39	364.82	433.71	68.89	427.59	44.39	364.82	433.71	68.89	429.82	–	–
1401	2.8	22,400	44.38	364.82	433.15	68.33	427.59	44.39	364.82	433.71	68.89	429.26	69.17-69.44	(0.27)
22241	3.0	24,000	46.36	370.93	459.26	88.33	451.48	45.57	370.93	454.26	83.33	450.37	82.00-82.78	(0.78)
17793	3.0	24,000	46.27	372.04	459.82	87.78	452.04	45.51	372.04	454.82	82.78	450.93	–	–
15569	3.0	24,000	46.24	372.59	459.82	87.23	452.59	45.51	372.59	455.37	82.78	451.48	–	–
13345	3.0	24,000	46.14	374.82	461.48	86.66	453.71	45.46	374.82	456.48	81.66	453.15	–	–
11121	3.0	24,000	46.11	374.26	460.37	86.11	453.15	45.40	374.26	455.93	81.67	452.59	–	–
8896	3.0	24,000	46.11	374.26	460.37	86.11	453.15	45.38	374.26	455.93	81.67	453.15	–	–
7784	3.0	24,000	46.01	374.26	459.82	85.56	452.59	45.39	374.26	455.93	81.67	452.59	–	–
6672	3.0	24,000	46.06	374.82	459.82	85.00	453.15	45.40	374.82	455.93	81.11	454.26	–	–
5560	3.0	24,000	45.93	374.82	459.82	85.00	452.59	45.32	374.82	455.93	81.11	452.59	–	–
4893	3.0	24,000	44.93	374.26	452.59	78.33	446.48	44.76	374.26	451.48	77.22	447.04	–	–
4448	3.0	24,000	44.79	372.59	450.37	77.78	443.71	44.69	372.59	449.26	76.67	444.82	75.78-76.11	(0.33)
4204	3.0	24,000	44.40	372.04	448.15	76.11	442.04	44.40	372.04	447.59	75.55	443.15	–	–
3736	3.0	24,000	44.39	371.48	447.59	76.11	441.48	44.40	371.48	447.04	75.56	442.59	–	–
3269	3.0	24,000	44.40	371.48	447.04	75.56	441.48	44.42	371.48	447.04	75.56	442.04	–	–
2802	3.0	24,000	44.27	370.93	447.04	76.11	440.93	44.30	370.93	446.48	75.55	442.04	–	–
2335	3.0	24,000	44.30	370.37	445.93	75.56	439.82	44.31	370.37	445.93	75.56	440.93	74.55-74.94	(0.39)
1868	3.0	24,000	44.20	370.37	445.93	75.56	439.82	44.24	370.37	445.37	75.00	440.93	–	–
1637	3.0	24,000	44.21	370.37	445.37	75.00	439.26	44.24	370.37	445.37	75.00	440.93	–	–
1401	3.0	24,000	44.07	369.82	444.26	74.44	438.71	44.15	369.82	444.26	74.44	439.82	74.22-74.44	(0.22)

* Cage speed expressed as a percent of shaft rpm.
** Bearing outer-race oil inlet ΔT measured directly by a supplementary circuit for determining thermal stability.

TABLE X
TASK III SKID STUDY
SOLID-BALL BEARING
200°F OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN52575 S/N 2560A-2					NO. 1 BEARING (FRONT) P/N SKN5257F S/N 2560A-1						
(1) Thrust Load (lb)	(2) DN x 10^6	(3) Shaft Speed (rpm)	(4) Cage Speed Percent*	(5) Oil Inlet Temp (°F)	(6) Avg. Outer Race Temp (°F)	(7) Outer Race Oil Inlet ΔT (°F)	(8) Avg. Oil Outlet Temp (°F)	(9) Cage Speed Percent*	(10) Oil Inlet Temp (°F)	(11) Avg. Outer Race Temp (°F)	(12) Outer Race Oil Inlet ΔT (°F)	(13) Avg. Oil Outlet Temp (°F)	(14) Outer Race - Oil Inlet Measured ΔT** (°F)	(15) Variation For a 5 Minute Time Period
5000	2.8	22,400	46.10	203	346	143	333	45.47	203	339	136	333	135.8 - 136.0	(0.2)
4000	2.8	22,400	45.96	203	347	144	334	45.38	203	339	136	333	–	–
3500	2.8	22,400	45.98	203	346	143	333	45.37	203	339	136	333	–	–
3000	2.8	22,400	45.88	203	341	138	330	45.28	203	336	133	330	131.0 - 132.5	(1.5)
2500	2.8	22,400	45.79	203	340	137	329	45.28	203	335	132	329	–	–
2000	2.8	22,400	45.65	203	338	135	328	45.22	203	333	130	328	–	–
1750	2.8	22,400	45.60	203	338	135	327	45.22	203	333	130	327	–	–
1500	2.8	22,400	45.48	202	336	134	327	45.22	202	332	130	327	–	–
1250	2.8	22,400	45.33	202	334	132	324	45.13	202	331	129	325	–	–
1100	2.8	22,400	45.08	201	331	130	322	45.08	201	329	128	323	–	–
1000	2.8	22,400	45.01	201	331	130	320	45.01	201	328	127	322	127.8 - 128.0	(0.2)
945	2.8	22,400	45.00	200	330	130	319	45.03	200	327	127	321	–	–
840	2.8	22,400	44.95	200	329	129	319	44.95	200	327	127	321	–	–
735	2.8	22,400	44.90	200	328	128	318	44.90	200	326	126	320	–	–
630	2.8	22,400	44.85	199	328	129	317	44.85	199	326	127	320	–	–
525	2.8	22,400	44.39	199	323	124	312	44.39	199	323	124	315	–	–
420	2.8	22,400	44.39	198	321	123	311	44.39	198	322	124	313	–	–
368	2.8	22,400	44.39	197	321	124	310	44.39	197	321	124	314	–	–
315	2.8	22,400	44.38	197	320	123	310	44.39	197	321	124	313	124.5 - 125.0	(0.5)
5000	3.0	24,000	46.36	208	367	159	353	45.57	208	358	150	351	147.6 - 149.0	(1.4)
4000	3.0	24,000	46.27	210	368	158	354	45.51	210	359	149	352	–	–
3500	3.0	24,000	46.24	211	368	157	355	45.51	211	360	149	353	–	–
3000	3.0	24,000	46.14	215	371	156	357	45.46	215	362	147	356	–	–
2500	3.0	24,000	46.11	214	369	155	356	45.40	214	361	147	355	–	–
2000	3.0	24,000	46.11	214	369	155	356	45.38	214	361	147	356	–	–
1750	3.0	24,000	46.01	214	368	154	355	45.39	214	361	147	355	–	–
1500	3.0	24,000	46.06	215	368	153	356	45.40	215	361	146	358	–	–
1250	3.0	24,000	45.93	215	369	153	355	45.32	215	361	146	355	–	–
1100	3.0	24,000	44.93	214	355	141	344	44.76	214	353	139	345	–	–
1000	3.0	24,000	44.79	211	351	140	339	44.69	211	349	138	341	136.4 - 137.0	(0.6)
945	3.0	24,000	44.40	210	347	137	336	44.40	210	346	136	338	–	–
840	3.0	24,000	44.39	209	346	137	335	44.40	209	345	136	337	–	–
735	3.0	24,000	44.40	209	345	136	335	44.42	209	345	136	336	–	–
630	3.0	24,000	44.27	208	345	137	334	44.30	208	344	136	336	–	–
525	3.0	24,000	44.30	207	343	136	332	44.31	207	343	136	334	134.2 - 134.9	(0.7)
420	3.0	24,000	44.20	207	343	136	332	44.24	207	342	135	334	–	–
368	3.0	24,000	44.21	207	342	135	331	44.24	207	342	135	334	–	–
315	3.0	24,000	44.07	206	340	134	330	44.15	206	340	134	332	133.6 - 134.0	(0.4)

* Cage speed is expressed as percent of shaft rpm.

** Bearing outer-race oil inlet ΔT is measured directly by a supplementary circuit for determining thermal stability.

TABLE XI
TASK III SKID STUDY
SOLID-BALL BEARING
FIRST AND SECOND REPEAT RUN - 3.0 MILLION DN
366.5°K OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN52575 S/N 2560A-2					NO. 1 BEARING (FRONT) P/N SKN52575 S/N 2560A-1						
(1) Thrust Load (newtons)	(2) DN x 10^6	(3) Shaft Speed (rpm)	(4) Cage Speed Percent*	(5) Oil Inlet Temp (°K)	(6) Avg. Outer Race Temp (°K)	(7) Outer Race Oil Inlet ΔT (°K)	(8) Avg. Oil Outlet Temp (°K)	(9) Cage Speed Percent*	(10) Oil Inlet Temp (°K)	(11) Avg. Outer Race Temp (°K)	(12) Outer Race Oil Inlet ΔT (°K)	(13) Avg. Oil Outlet Temp (°K)	(14) Outer Race - Oil Inlet Measured ΔT**(°K) Variation For a 5 Minute Time Period	(15)
22241	3.0	24,000	45.63	364.82	447.59	82.77	443.71	44.88	364.82	443.15	78.33	438.15	78.33-78.94	(0.61)
17793	3.0	24,000	45.63	365.93	447.59	81.66	443.71	44.95	365.93	443.15	77.22	438.15	–	–
13344	3.0	24,000	45.49	366.48	447.59	81.11	444.26	44.76	366.48	443.71	77.23	438.71	–	–
9341	3.0	24,000	45.35	366.48	448.15	81.67	443.71	44.65	366.48	443.71	77.23	438.71	–	–
8896	3.0	24,000	45.35	367.04	447.59	80.55	444.82	44.73	367.04	443.71	76.67	438.71	–	–
8407	3.0	24,000	45.31	367.04	447.59	80.55	443.71	44.69	367.04	443.71	76.67	438.71	–	–
7940	3.0	24,000	45.32	367.04	447.04	80.00	443.71	44.68	367.04	443.71	76.67	438.71	–	–
7473	3.0	24,000	45.36	367.04	447.59	80.55	443.71	44.70	367.04	443.15	76.11	438.71	–	–
7006	3.0	24,000	45.35	367.04	447.59	80.55	443.71	44.74	367.04	443.15	76.11	438.71	–	–
6539	3.0	24,000	45.30	367.04	447.59	80.55	443.15	44.68	367.04	443.15	76.11	438.71	–	–
6316	3.0	24,000	45.27	367.04	447.04	80.00	443.15	44.64	367.04	443.15	76.11	438.71	–	–
6072	3.0	24,000	45.21	367.04	447.04	80.00	442.59	44.63	367.04	443.15	76.11	438.15	–	–
5605	3.0	24,000	45.21	367.04	446.48	79.44	442.59	44.63	367.04	442.59	75.55	438.15	–	–
5382	3.0	24,000	45.18	366.48	447.04	80.56	442.59	44.61	366.48	442.59	76.11	438.15	–	–
5138	3.0	24,000	45.17	366.48	446.48	80.00	442.59	44.58	366.48	442.59	76.11	437.59	–	–
4893	3.0	24,000	45.14	366.48	446.48	80.00	442.59	44.60	366.48	442.59	76.11	437.59	76.05-76.38	(0.33)
4671	3.0	24,000	45.10	367.04	446.48	79.44	442.59	44.58	367.04	442.59	75.55	437.59	–	–
4204	3.0	24,000	45.13	367.04	446.48	79.44	442.04	44.57	367.04	442.59	75.55	438.15	–	–
3736	3.0	24,000	45.04	367.04	445.93	78.89	439.26	44.51	367.04	442.04	75.00	437.59	–	–
3269	3.0	24,000	44.99	367.04	445.93	78.89	439.26	44.46	367.04	442.04	75.00	437.59	–	–
2802	3.0	24,000	44.87	367.04	445.37	78.33	439.26	44.36	367.04	441.48	74.44	437.04	–	–
2335	3.0	24,000	44.86	366.48	444.82	78.34	440.93	44.36	366.48	441.48	75.00	436.98	–	–
1868	3.0	24,000	44.40	366.48	441.48	75.00	438.15	44.10	366.48	439.26	72.78	434.26	–	–
22241	3.0	24,000	45.37	366.48	448.71	82.23	444.82	44.70	366.48	443.71	77.23	437.59	76.33-76.83	(0.50)
17793	3.0	24,000	45.37	367.04	448.71	81.67	444.82	44.71	367.04	443.71	76.67	439.26	–	–
13344	3.0	24,000	45.35	367.59	448.71	81.12	444.82	44.69	367.59	444.26	76.67	439.26	–	–
9341	3.0	24,000	45.25	367.59	448.71	81.12	444.26	44.63	367.59	443.71	76.12	438.71	–	–
8896	3.0	24,000	45.20	367.59	448.71	81.12	444.26	44.61	367.59	443.71	76.12	438.71	–	–
8407	3.0	24,000	45.21	367.04	448.15	81.11	443.71	44.58	367.04	443.15	76.11	438.71	–	–
7940	3.0	24,000	45.24	367.04	447.59	80.55	444.26	44.63	367.04	443.15	76.11	438.71	–	–
7473	3.0	24,000	45.24	367.04	448.15	81.11	444.26	44.64	367.04	443.15	76.11	438.71	–	–
7006	3.0	24,000	45.27	367.04	448.15	81.11	443.71	44.65	367.04	443.15	76.11	438.71	–	–
6539	3.0	24,000	45.25	367.04	447.59	81.11	443.71	44.62	367.04	443.15	76.11	438.71	–	–
6072	3.0	24,000	45.24	367.04	447.04	80.00	443.71	44.58	367.04	442.59	75.55	438.15	–	–
5605	3.0	24,000	45.20	367.04	447.59	81.11	443.15	44.62	367.04	443.15	76.11	438.15	–	–
5382	3.0	24,000	45.18	367.04	447.04	80.00	443.15	44.61	367.04	442.59	75.55	438.15	–	–
5138	3.0	24,000	45.17	367.04	447.04	80.00	443.15	44.61	367.04	442.59	75.55	438.15	–	–
4893	3.0	24,000	45.12	366.48	446.48	80.00	442.59	44.55	366.48	442.59	76.11	437.59	76.16-76.72	(0.56)
4671	3.0	24,000	45.14	367.04	447.04	80.00	442.59	44.57	367.04	442.59	75.55	438.15	–	–
4204	3.0	24,000	45.05	366.48	445.93	79.45	442.04	44.52	366.48	442.04	75.56	437.59	–	–
3736	3.0	24,000	45.00	366.48	445.93	79.45	442.59	44.48	366.48	442.04	75.56	437.59	–	–
3269	3.0	24,000	44.63	366.48	443.71	77.23	440.37	44.18	366.48	440.37	73.89	435.37	–	–
2802	3.0	24,000	44.69	366.48	443.71	77.23	439.82	44.24	366.48	440.37	73.89	435.37	74.16-74.55	(0.39)
2335	3.0	24,000	44.73	365.93	443.15	77.22	439.82	44.24	365.93	439.82	73.89	434.82	–	–
1868	3.0	24,000	44.40	365.93	442.04	76.11	439.26	44.04	365.93	438.71	72.78	433.71	–	–

* Cage speed expressed as a percent of shaft rpm.

** Bearing outer-race oil inlet ΔT is measured directly by a supplementary circuit for determining thermal stability.

TABLE XII
TASK III SKID STUDY
SOLID-BALL BEARING
FIRST AND SECOND REPEAT TESTS - 3.0 MILLION DN
200°F OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN52575 S/N 2560A-2					NO. 1 BEARING (FRONT) P/N SKN52575 S/N 2560A-1						
(1) Thrust Load (lb)	(2) DN x 10^6	(3) Shaft Speed (rpm)	(4) Cage Speed Percent*	(5) Oil Inlet Temp (°F)	(6) Avg. Outer Race Temp (°F)	(7) Outer Race Oil Inlet ΔT (°F)	(8) Avg. Oil Outlet Temp (°F)	(9) Cage Speed Percent*	(10) Oil Inlet Temp (°F)	(11) Avg. Outer Race Temp (°F)	(12) Outer Race Oil Inlet ΔT (°F)	(13) Avg. Oil Outlet Temp (°F)	(14) Outer Race - Oil Inlet Measured ΔT** (°F) Variation For A 5 Minute Time Period	(15)
5000	3.0	24,000	45.63	197	346	149	339	44.88	197	338	141	329	141.0 - 142.1	(1.1)
4000	3.0	24,000	45.63	199	346	147	339	44.95	199	338	139	329	–	–
3000	3.0	24,000	45.49	200	346	146	340	44.76	200	339	139	330	–	–
2100	3.0	24,000	45.35	200	347	147	339	44.65	200	339	139	330	–	–
2000	3.0	24,000	45.35	201	346	145	341	44.73	201	339	138	330	–	–
1890	3.0	24,000	45.31	201	346	145	339	44.69	201	339	138	330	–	–
1785	3.0	24,000	45.32	201	345	144	339	44.68	201	339	138	330	–	–
1680	3.0	24,000	45.36	201	346	145	339	44.70	201	338	137	330	–	–
1575	3.0	24,000	45.35	201	346	145	339	44.74	201	338	137	330	–	–
1470	3.0	24,000	45.30	201	346	145	338	44.68	201	338	137	330	–	–
1420	3.0	24,000	45.27	201	345	144	338	44.64	201	338	137	330	–	–
1365	3.0	24,000	45.21	201	345	144	337	44.63	201	338	137	329	–	–
1260	3.0	24,000	45.21	201	344	143	337	44.63	201	337	136	329	–	–
1210	3.0	24,000	45.18	200	345	145	337	44.61	200	337	137	329	–	–
1155	3.0	24,000	45.17	200	344	144	337	44.58	200	337	137	328	–	–
1100	3.0	24,000	45.14	200	344	144	337	44.60	200	337	137	328	136.9 - 137.5	(0.6)
1050	3.0	24,000	45.10	201	344	143	337	44.58	201	337	136	328	–	–
945	3.0	24,000	45.13	201	344	143	336	44.57	201	337	136	329	–	–
840	3.0	24,000	45.04	201	343	142	331	44.51	201	336	135	328	–	–
735	3.0	24,000	44.99	201	343	142	331	44.46	201	336	135	328	–	–
630	3.0	24,000	44.87	201	342	141	331	44.36	201	335	134	327	–	–
525	3.0	24,000	44.86	200	341	141	334	44.36	200	335	135	326	–	–
420	3.0	24,000	44.40	200	335	135	329	44.10	200	331	131	322	–	–
5000	3.0	24,000	45.37	200	348	148	341	44.70	200	339	139	328	137.4 - 138.3	(0.9)
4000	3.0	24,000	45.37	201	348	147	341	44.71	201	339	138	331	–	–
3000	3.0	24,000	45.35	202	348	146	341	44.69	202	340	138	331	–	–
2100	3.0	24,000	45.25	202	348	146	340	44.63	202	339	137	330	–	–
2000	3.0	24,000	45.20	202	348	146	340	44.61	202	339	137	330	–	–
1890	3.0	24,000	45.21	201	347	146	339	44.58	201	338	137	330	–	–
1785	3.0	24,000	45.24	201	346	145	340	44.63	201	338	137	330	–	–
1680	3.0	24,000	45.24	201	347	146	340	44.64	201	338	137	330	–	–
1575	3.0	24,000	45.27	201	347	146	339	44.66	201	338	137	330	–	–
1470	3.0	24,000	45.25	201	346	145	339	44.62	201	338	137	330	–	–
1365	3.0	24,000	45.24	201	345	144	339	44.58	201	337	136	329	–	–
1260	3.0	24,000	45.20	201	346	145	338	44.62	201	338	137	329	–	–
1210	3.0	24,000	45.18	201	345	144	338	44.61	201	337	136	329	–	–
1155	3.0	24,000	45.17	201	345	144	338	44.61	201	337	136	329	–	–
1100	3.0	24,000	45.12	200	344	144	337	44.66	200	337	137	328	137.1 - 138.1	(1.0)
1050	3.0	24,000	45.14	201	345	144	337	44.57	201	337	136	329	–	–
945	3.0	24,000	45.05	200	343	143	336	44.62	200	336	136	328	–	–
840	3.0	24,000	45.00	200	343	143	337	44.48	200	336	136	328	–	–
735	3.0	24,000	44.63	200	339	139	333	44.18	200	333	133	324	–	–
630	3.0	24,000	44.69	200	339	139	332	44.24	200	333	133	324	133.5 - 134.2	(0.7)
525	3.0	24,000	44.73	199	338	139	332	44.24	199	332	133	323	–	–
420	3.0	24,000	44.40	199	336	137	331	44.04	199	330	131	321	–	–

* Cage speed is expressed as percent of shaft rpm.

** Bearing outer-race oil inlet ΔT is measured directly by a supplementary circuit for determining thermal stability

TABLE XIII
TASK III SKID STUDY
SOLID-BALL BEARING
388.7°K OIL INLET TEMPERATURE

(1) Thrust Load (newtons)	(2) DN x 10^6	(3) Shaft Speed (rpm)	NO. 2 BEARING (REAR) P/N SKN52575 S/N 2560A-2 (4) Cage Speed Percent*	(5) Oil Inlet Temp (°K)	(6) Avg. Outer Race Temp (°K)	(7) Outer Race Oil Inlet ΔT (°K)	(8) Avg. Oil Outlet Temp (°K)	NO. 1 BEARING (FRONT) P/N SKN52575 S/N 2560A-2 (9) Cage Speed Percent*	(10) Oil Inlet Temp (°K)	(11) Avg. Outer Race Temp (°K)	(12) Outer Race Oil Inlet ΔT (°K)	(13) Avg. Oil Outlet Temp (°K)	(14) Outer Race - Oil Inlet Measured ΔT** (°K) Variation For a 5 Minute Time Period	(15)
22241	1.0	8,000	44.61	387.04	402.59	15.55	398.71	44.54	387.04	402.59	15.55	399.26	15.77-15.88	(0.11)
17793	1.0	8,000	44.71	387.04	402.59	15.55	398.71	44.68	387.04	402.04	15.00	399.26	–	–
15569	1.0	8,000	44.75	387.59	403.15	15.56	399.26	44.71	387.59	403.15	15.56	399.82	–	–
13344	1.0	8,000	44.64	387.59	403.15	15.56	399.82	44.61	387.59	403.15	15.56	399.82	–	–
11121	1.0	8,000	44.75	388.71	403.71	15.00	400.93	44.71	388.71	403.71	15.00	400.93	–	–
8896	1.0	8,000	44.79	387.59	403.15	15.56	399.26	44.75	387.59	403.15	15.56	399.82	–	–
7784	1.0	8,000	44.46	387.04	402.59	15.55	398.71	44.39	387.04	402.59	15.55	399.26	–	–
6672	1.0	8,000	44.50	387.59	403.15	15.56	399.26	44.46	387.59	403.15	15.56	399.26	–	–
5560	1.0	8,000	44.79	388.15	403.15	15.00	399.26	44.75	388.15	403.15	15.00	399.82	–	–
4893	1.0	8,000	44.43	388.15	403.71	15.56	399.26	44.39	388.15	403.71	15.56	399.82	–	–
4448	1.0	8,000	44.93	388.71	403.71	15.00	399.82	44.86	388.71	403.71	15.00	400.37	14.88-15.05	(0.17)
4204	1.0	8,000	44.93	388.71	403.71	15.00	399.82	44.86	388.71	403.71	15.00	399.82	–	–
3736	1.0	8,000	44.75	388.71	403.71	15.00	399.82	44.71	388.71	403.71	15.00	400.37	–	–
3269	1.0	8,000	44.79	388.71	403.71	15.00	399.82	44.68	388.71	403.71	15.00	400.37	–	–
2802	1.0	8,000	44.82	388.71	403.71	15.00	399.82	44.71	388.71	403.71	15.00	399.82	–	–
2335	1.0	8,000	44.82	389.26	403.71	14.45	399.82	44.75	389.26	403.71	14.45	400.37	–	–
1868	1.0	8,000	44.86	389.26	403.15	13.89	399.26	44.75	389.26	403.15	13.89	399.82	–	–
1636	1.0	8,000	44.86	388.71	403.15	14.44	399.26	44.79	388.71	403.15	14.44	399.82	13.94-14.22	(0.28)
22241	1.5	12,000	45.71	388.15	415.93	27.78	410.93	45.45	388.15	414.26	26.11	411.48	25.66-26.44	(0.78)
17793	1.5	12,000	45.69	388.15	415.37	27.22	410.37	45.38	388.15	413.71	25.56	411.48	–	–
15569	1.5	12,000	45.62	388.15	415.37	27.22	410.37	45.33	388.15	413.71	25.56	411.48	–	–
13344	1.5	12,000	45.55	388.15	415.37	27.22	410.37	45.26	388.15	413.71	25.56	411.48	–	–
11121	1.5	12,000	45.69	388.71	415.37	26.66	410.93	45.38	388.71	414.26	25.55	411.48	–	–
8896	1.5	12,000	45.60	388.15	415.37	27.22	410.93	45.33	388.15	413.71	25.56	411.48	–	–
7784	1.5	12,000	45.76	388.15	415.37	27.22	410.37	45.45	388.15	413.71	25.56	410.93	–	–
6672	1.5	12,000	45.71	388.15	415.37	27.22	410.93	45.38	388.15	413.71	25.56	410.93	–	–
5560	1.5	12,000	45.64	388.15	415.37	27.22	410.93	45.36	388.15	413.71	25.56	411.48	–	–
4893	1.5	12,000	45.60	388.71	415.37	26.66	410.93	45.31	388.71	413.71	25.00	411.48	–	–
4448	1.5	12,000	45.76	388.71	415.37	26.66	410.93	45.45	388.71	414.26	25.55	411.48	24.94-25.11	(0.17)
4204	1.5	12,000	45.69	388.71	415.37	26.66	410.93	45.38	388.71	413.71	25.00	411.48	–	–
3736	1.5	12,000	45.57	388.71	414.82	26.11	410.37	45.29	388.71	413.71	25.00	411.48	–	–
3269	1.5	12,000	45.60	388.15	414.26	26.11	409.82	45.29	388.15	413.15	25.00	411.48	–	–
2802	1.5	12,000	45.60	388.71	414.82	26.11	409.82	45.31	388.71	413.71	25.00	411.48	–	–
2335	1.5	12,000	45.55	388.15	414.82	26.11	409.82	45.24	388.15	413.71	25.56	410.93	–	–
1868	1.5	12,000	45.67	388.15	414.82	26.11	409.82	45.33	388.15	413.71	25.56	410.93	–	–
1636	1.5	12,000	45.62	388.15	413.71	25.56	408.71	45.29	388.15	412.59	24.44	410.37	24.72-25.05	(0.33)

* Cage speed expressed as a percent of shaft rpm.

**Bearing outer-race oil inlet ΔT is measured directly by a supplementary circuit for determining thermal stability.

TABLE XIV
TASK III SKID STUDY
SOLID-BALL BEARING
240°F OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN52575 S/N 2560A-2					NO. 1 BEARING (FRONT) P/N SKN52575 S/N2560A-1						
(1) Thrust Load (lb)	(2) DN x 10^6	(3) Shaft Speed (rpm)	(4) Cage Speed Percent*	(5) Oil Inlet Temp (°F)	(6) Avg. Outer Race Temp (°F)	(7) Outer Race Oil Inlet ΔT (°F)	(8) Avg. Oil Outlet Temp (°F)	(9) Cage Speed Percent*	(10) Oil Inlet Temp (°F)	(11) Avg. Outer Race Temp (°F)	(12) Outer Race Oil Inlet ΔT (°F)	(13) Avg. Oil Outlet Temp (°F)	(14) Outer Race - Oil Inlet Measured ΔT** (°F) Variation For A 5 Minute Time Period	(15)
5000	1.0	8,000	44.61	237	265	29	258	44.54	237	265	29	259	28.4 - 28.6	(0.2)
4000	1.0	8,000	44.71	237	265	28	258	44.68	237	264	28	259	–	–
3500	1.0	8,000	44.75	238	266	28	259	44.71	238	266	28	260	–	–
3000	1.0	8,000	44.64	238	266	28	260	44.61	238	266	28	260	–	–
2500	1.0	8,000	44.75	240	267	27	262	44.71	240	267	27	262	–	–
2000	1.0	8,000	44.79	238	266	28	259	44.75	238	266	28	260	–	–
1750	1.0	8,000	44.46	237	265	28	258	44.39	237	265	28	259	–	–
1500	1.0	8,000	44.50	238	266	28	259	44.46	238	266	28	259	–	–
1250	1.0	8,000	44.79	239	266	27	259	44.75	239	266	27	260	–	–
1100	1.0	8,000	44.43	239	267	28	259	44.39	239	267	28	260	–	–
1000	1.0	8,000	44.93	240	267	27	260	44.86	240	267	27	261	26.8 - 27.1	(0.3)
945	1.0	8,000	44.93	240	267	27	260	44.86	240	267	27	260	–	–
840	1.0	8,000	44.75	240	267	27	260	44.71	240	267	27	261	–	–
735	1.0	8,000	44.79	240	267	27	260	44.68	240	267	27	261	–	–
630	1.0	8,000	44.82	240	267	27	260	44.71	240	267	27	260	–	–
525	1.0	8,000	44.82	241	267	26	260	44.75	241	267	26	261	–	–
420	1.0	8,000	44.86	241	266	25	259	44.75	241	266	25	260	–	–
368	1.0	8,000	44.86	240	266	26	259	44.79	240	266	26	260	25.1 - 25.6	(0.5)
5000	1.5	12,000	45.71	239	289	50	280	45.45	239	286	47	281	46.2 - 47.6	(1.4)
4000	1.5	12,000	45.69	239	288	49	279	45.38	239	285	46	281	–	–
3500	1.5	12,000	45.62	239	288	49	279	45.33	239	285	46	281	–	–
3000	1.5	12,000	45.55	239	288	49	279	45.26	239	285	46	281	–	–
2500	1.5	12,000	45.69	240	288	48	280	45.38	240	286	46	281	–	–
2000	1.5	12,000	45.60	239	288	49	280	45.33	239	285	46	281	–	–
1750	1.5	12,000	45.76	239	288	49	279	45.45	239	285	46	280	–	–
1500	1.5	12,000	45.71	239	288	49	280	45.38	239	285	46	280	–	–
1250	1.5	12,000	45.64	239	288	49	280	45.36	239	285	46	281	–	–
1100	1.5	12,000	45.60	240	288	48	280	45.31	240	285	45	281	–	–
1000	1.5	12,000	45.76	240	288	48	280	45.45	240	286	46	281	44.9 - 45.2	(0.3)
945	1.5	12,000	45.69	240	288	48	280	45.38	240	285	45	281	–	–
840	1.5	12,000	45.57	240	287	47	279	45.29	240	285	45	281	–	–
735	1.5	12,000	45.60	239	286	47	278	45.29	239	284	45	281	–	–
630	1.5	12,000	45.60	240	287	47	278	45.31	240	285	45	281	–	–
525	1.5	12,000	45.55	239	287	48	278	45.24	239	285	46	280	–	–
420	1.5	12,000	45.67	239	287	48	278	45.33	239	285	46	280	–	–
368	1.5	12,000	45.62	239	285	46	276	45.29	239	283	44	279	44.5 - 45.1	(0.6)

* Cage speed is expressed as percent of shaft rpm.

** Bearing outer-race oil inlet ΔT is measured directly by a supplementary circuit for determining thermal stability

TABLE XV
TASK III SKID STUDY
SOLID-BALL BEARING
388.7°K OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN52575 S/N 2560A-2					NO. 1 BEARING (FRONT) P/N SKN52575 S/N 2560A-1						
(1) Thrust Load (newtons)	(2) DN x 10^6	(3) Shaft Speed (rpm)	(4) Cage Speed Percent*	(5) Oil Inlet Temp (°K)	(6) Avg. Outer Race Temp (°K)	(7) Outer Race Oil Inlet ΔT (°K)	(8) Avg. Oil Outlet Temp (°K)	(9) Cage Speed Percent*	(10) Oil Inlet Temp (°K)	(11) Avg. Outer Race Temp (°K)	(12) Outer Race Oil Inlet ΔT (°K)	(13) Avg. Oil Outlet Temp (°K)	(14) Outer Race - Oil Inlet Measured ΔT** (°K)	(15) Variation For a 5 Minute Time Period
22241	2.0	16,000	46.02	388.71	435.37	46.66	428.71	45.50	388.71	433.71	45.00	429.82	43.94-44.22	(0.28)
17793	2.0	16,000	47.07	388.15	434.82	46.67	428.71	45.55	388.15	433.15	45.00	429.82	–	–
15569	2.0	16,000	47.07	388.15	434.82	46.67	428.71	45.55	388.15	433.15	45.00	429.82	–	–
13344	2.0	16,000	46.05	388.15	434.26	46.11	428.71	45.54	388.15	432.59	44.44	429.26	–	–
11121	2.0	16,000	45.96	388.15	434.26	46.11	428.15	45.45	388.15	432.59	44.44	429.26	–	–
8896	2.0	16,000	45.89	388.15	433.71	45.56	427.59	45.37	388.15	432.04	43.89	428.71	–	–
7784	2.0	16,000	46.02	388.15	433.71	45.56	428.15	45.52	388.15	431.48	43.33	428.71	–	–
6672	2.0	16,000	46.05	388.15	433.15	45.00	427.59	45.52	388.15	431.48	43.33	428.71	–	–
5560	2.0	16,000	46.00	388.15	432.04	43.89	427.04	45.48	388.15	430.93	42.78	427.59	–	–
4893	2.0	16,000	45.93	388.15	431.48	43.43	426.48	45.41	388.15	429.82	41.67	427.04	–	–
4448	2.0	16,000	45.89	388.15	430.93	42.78	426.48	45.36	388.15	429.26	41.11	427.04	41.88-42.27	(0.39)
4204	2.0	16,000	46.07	388.71	431.48	42.77	427.04	45.54	388.71	429.82	41.11	427.04	–	–
3736	2.0	16,000	45.91	388.15	430.93	42.78	426.48	45.36	388.15	429.26	41.11	426.48	–	–
3269	2.0	16,000	45.80	388.15	430.37	42.22	425.93	45.27	388.15	428.71	40.56	425.93	–	–
2802	2.0	16,000	45.86	388.15	429.82	41.67	425.37	45.32	388.15	428.15	40.00	425.37	–	–
2335	2.0	16,000	45.84	388.15	429.82	41.67	424.82	45.27	388.15	427.59	39.44	425.37	–	–
1868	2.0	16,000	45.77	388.15	428.71	40.56	424.26	45.23	388.15	427.04	38.89	424.82	–	–
1636	2.0	16,000	45.70	388.15	428.71	40.56	424.26	45.14	388.15	427.04	38.89	424.82	39.55-39.77	(0.22)
22241	2.4	19,200	46.13	388.71	446.48	57.77	438.71	45.54	388.71	444.26	55.55	440.37	54.88-55.44	(0.56)
17793	2.4	19,200	45.79	388.71	443.71	55.00	437.04	45.27	388.71	441.48	52.77	438.15	–	–
15569	2.4	19,200	45.71	389.26	443.71	54.45	437.04	45.25	389.26	442.04	52.78	438.71	–	–
13344	2.4	19,200	45.71	389.26	443.71	54.45	437.04	45.25	389.26	442.04	52.78	438.71	–	–
11121	2.4	19,200	45.54	389.26	443.15	53.89	436.48	45.15	389.26	441.48	52.22	438.15	–	–
8896	2.4	19,200	45.52	389.26	443.15	53.89	436.48	45.13	389.26	441.48	52.22	438.15	–	–
7784	2.4	19,200	45.49	389.26	442.59	53.33	436.48	45.12	389.26	441.48	52.22	438.15	–	–
6672	2.4	19,200	45.39	388.15	440.93	52.78	435.37	45.06	388.15	440.93	52.78	437.59	–	–
5560	2.4	19,200	45.28	388.15	440.93	52.78	435.37	44.96	388.15	440.93	52.78	437.59	–	–
4893	2.4	19,200	45.25	388.15	440.93	52.78	435.37	44.97	388.15	440.93	52.78	437.59	–	–
4448	2.4	19,200	45.24	388.15	440.37	52.22	434.82	44.93	388.15	440.93	52.78	437.04	52.27-52.55	(0.28)
4204	2.4	19,200	45.25	388.15	440.37	52.22	434.82	44.96	388.15	440.37	52.22	437.04	–	–
3736	2.4	19,200	45.16	388.15	440.37	52.22	434.82	44.85	388.15	440.37	52.22	437.04	–	–
3269	2.4	19,200	45.15	388.15	440.37	52.22	434.82	44.90	388.15	440.37	52.22	437.04	–	–
2802	2.4	19,200	45.12	388.15	440.37	52.22	434.82	44.85	388.15	440.37	52.22	437.04	–	–
2335	2.4	19,200	45.10	388.15	439.82	51.67	434.26	44.85	388.15	439.82	51.67	436.48	–	–
1868	2.4	19,200	45.12	388.15	439.82	51.67	434.26	44.85	388.15	439.82	51.67	436.48	–	–
1636	2.4	19,200	45.06	388.15	439.26	51.11	434.26	44.84	388.15	439.26	51.11	436.48	51.72-52.11	(0.39)

* Cage speed expressed as a percent of shaft rpm.
**Bearing outer-race oil inlet ΔT is measured directly by a supplementary circuit for determining thermal stability.

TABLE XVI
TASK III SKID STUDY
SOLID-BALL BEARING
240°F OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN52575 S/N 2560A-2					NO. 1 BEARING (FRONT) P/N SKN52575 S/N 2560-1						
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Thrust Load (lb)	DN x 10^6	Shaft Speed (rpm)	Cage Speed Percent*	Oil Inlet Temp (°F)	Avg. Outer Race Temp (°F)	Outer Race Oil Inlet ΔT (°F)	Avg. Oil Outlet Temp (°F)	Cage Speed Percent*	Oil Inlet Temp (°F)	Avg. Outer Race Temp (°F)	Outer Race Oil Inlet ΔT (°F)	Avg. Oil Outlet Temp (°F)	Outer Race - Oil Inlet Measured ΔT** (°F) Variation For A 5 Minute Time Period	
5000	2.0	16,000	46.02	240	324	84	312	45.50	240	321	81	314	79.1 - 79.6	(0.5)
4000	2.0	16,000	46.07	239	323	84	312	45.55	239	320	81	314	–	–
3500	2.0	16,000	46.07	239	323	84	312	45.55	239	320	81	314	–	–
3000	2.0	16,000	46.05	239	322	83	312	45.54	239	319	80	313	–	–
2500	2.0	16,000	45.96	239	322	83	311	45.45	239	319	80	313	–	–
2000	2.0	16,000	45.89	239	321	82	310	45.37	239	318	79	312	–	–
1750	2.0	16,000	46.02	239	321	82	311	45.52	239	317	78	312	–	–
1500	2.0	16,000	46.05	239	320	81	310	45.52	239	317	78	312	–	–
1250	2.0	16,000	46.00	239	318	79	309	45.48	239	316	77	310	–	–
1100	2.0	16,000	45.93	239	317	78	308	45.41	239	314	75	309	–	–
1000	2.0	16,000	45.89	239	316	77	308	45.36	239	313	74	309	75.4 - 76.1	(0.7)
945	2.0	16,000	46.07	240	317	77	309	45.54	240	314	74	309	–	–
840	2.0	16,000	45.91	239	316	77	308	45.36	239	313	74	308	–	–
735	2.0	16,000	45.80	239	315	76	307	45.27	239	312	73	307	–	–
630	2.0	16,000	45.86	239	314	75	306	45 32	239	311	72	306	–	–
525	2.0	16,000	45.84	239	314	75	305	45.27	239	310	71	306	–	–
420	2.0	16,000	45.77	239	312	73	304	45.23	239	309	70	305	–	–
368	2.0	16,000	45.70	239	312	73	304	45.14	239	309	70	305	71.2 - 71.6	(0.4)
5000	2.4	19,200	46.13	240	344	104	330	45.54	240	340	100	333	98.8 - 99.8	(1.0)
4000	2.4	19,200	45.79	240	339	99	327	45.27	240	335	95	329	–	–
3500	2.4	19,200	45.71	241	339	98	327	45.25	241	336	95	330	–	–
3000	2.4	19,200	45.71	241	339	98	327	45.25	241	336	95	330	–	–
2500	2.4	19,200	45.54	241	338	97	326	45.15	241	335	94	329	–	–
2000	2.4	19,200	45.52	241	338	97	326	45.13	241	335	94	329	–	–
1750	2.4	19,200	45.49	241	337	96	326	45.12	241	335	94	329	–	–
1500	2.4	19,200	45.39	239	334	95	324	45.06	239	334	95	328	–	–
1250	2.4	19,200	45.28	239	334	95	324	44.96	239	334	95	328	–	–
1100	2.4	19,200	45.25	239	334	95	324	44.97	239	334	95	328	–	–
1000	2.4	19,200	45.24	239	333	94	323	44.93	239	334	94	327	94.1 - 94.6	(0.5)
945	2.4	19,200	45.25	239	333	94	323	44.96	239	333	94	327	–	–
840	2.4	19,200	45.16	239	333	94	323	44.85	239	333	94	327	–	–
735	2.4	19,200	45.15	239	333	94	323	44.90	239	333	94	327	–	–
630	2.4	19,200	45.12	239	333	94	323	44.85	239	333	94	327	–	–
525	2.4	19,200	45.10	239	332	93	322	44.85	239	332	93	326	–	–
420	2.4	19,200	45.12	239	332	93	322	44.85	239	332	93	326	–	–
368	2.4	19,200	45.06	239	331	92	322	44.84	239	331	92	326	93.1 - 93.8	(0.7)

* Cage speed is expressed as percent of shaft rpm.

** Bearing outer-race oil inlet ΔT is measured directly by a supplementary circuit for determining thermal stability.

TABLE XVII
TASK III SKID STUDY
SOLID-BALL BEARING
388.7°K OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN52575 S/N 2560A-2					NO. 1 BEARING (FRONT) P/N SKN52575 S/N 2560A-1						
(1) Thrust Load (newtons)	(2) DN x 10^6	(3) Shaft Speed (rpm)	(4) Cage Speed Percent*	(5) Oil Inlet Temp (°K)	(6) Avg. Outer Race Temp (°K)	(7) Outer Race Oil Inlet ΔT (°K)	(8) Avg. Oil Outlet Temp (°K)	(9) Cage Speed Percent*	(10) Oil Inlet Temp (°K)	(11) Avg. Outer Race Temp (°K)	(12) Outer Race Oil Inlet ΔT (°K)	(13) Avg. Oil Outlet Temp (°K)	(14) Outer Race - Oil Inlet Measured ΔT** (°K) Variation For a 5 Minute Time Period	(15)
22241	2.8	22,400	46.34	389.82	464.26	74.44	457.04	45.56	389.82	460.37	70.55	457.04	69.77-70.50	(0.73)
17793	2.8	22,400	46.29	389.82	463.15	73.33	456.48	45.50	389.82	460.37	70.55	457.04	–	–
15569	2.8	22,400	46.25	389.82	462.59	72.77	455.93	45.45	389.82	459.26	69.44	456.48	–	–
13344	2.8	22,400	46.15	389.82	461.48	71.66	455.37	45.40	389.82	459.26	69.44	455.37	–	–
11121	2.8	22,400	46.19	389.26	460.93	71.67	454.82	45.41	389.26	458.71	69.45	455.37	–	–
8896	2.8	22,400	45.98	389.26	459.82	70.56	454.26	45.34	389.26	457.59	68.33	454.26	–	–
7784	2.8	22,400	45.85	388.71	458.71	70.00	453.15	45.28	388.71	457.04	68.33	453.71	–	–
6672	2.8	22,400	45.64	388.15	457.04	68.89	451.48	45.22	388.15	456.48	68.33	452.59	–	–
5560	2.8	22,400	45.29	388.15	455.37	67.22	449.82	45.10	388.15	454.82	66.67	451.48	–	–
4893	2.8	22,400	45.26	388.15	455.37	67.22	449.26	45.08	388.15	455.37	67.22	451.48	–	–
4448	2.8	22,400	45.09	388.15	454.26	66.11	448.71	45.04	388.15	454.26	66.11	450.93	65.44-65.83	(0.39)
4204	2.8	22,400	44.94	388.15	453.71	65.56	448.71	44.92	388.15	453.71	65.56	450.37	–	–
3736	2.8	22,400	44.86	387.59	453.15	65.56	448.15	44.89	387.59	453.15	65.56	450.37	–	–
3269	2.8	22,400	44.80	388.15	453.71	65.56	448.71	44.83	388.15	453.71	65.56	450.37	–	–
2802	2.8	22,400	44.69	388.15	453.15	65.00	448.15	44.69	388.15	453.71	65.56	449.82	–	–
2335	2.8	22,400	44.36	388.71	450.93	62.22	445.93	44.39	388.71	452.04	63.33	448.71	–	–
1868	2.8	22,400	44.35	388.15	450.37	62.22	445.93	44.41	388.15	451.48	63.33	448.15	–	–
1636	2.8	22,400	44.16	388.15	449.82	61.67	444.82	44.34	388.15	450.93	62.78	446.48	62.39-63.39	(1.00)
22241	3.0	24,000	46.00	390.37	469.26	78.89	463.15	45.36	390.37	468.15	77.78	464.26	75.61-76.39	(0.78)
17793	3.0	24,000	45.95	390.37	469.26	78.89	463.15	45.29	390.37	467.04	76.67	463.71	–	–
15569	3.0	24,000	45.86	390.37	468.71	78.34	462.59	45.21	390.37	465.93	75.56	463.15	–	–
13344	3.0	24,000	45.80	390.37	468.71	78.34	462.04	45.21	390.37	466.48	76.11	462.59	–	–
11121	3.0	24,000	45.77	390.37	468.15	77.78	462.04	45.18	390.37	465.93	75.56	462.59	–	–
8896	3.0	24,000	45.74	390.37	467.59	77.22	462.04	45.14	390.37	465.93	75.56	462.59	–	–
7784	3.0	24,000	45.74	390.37	467.59	77.22	461.48	45.19	390.37	465.37	75.00	462.04	–	–
6672	3.0	24,000	45.69	390.37	467.59	77.22	462.04	45.19	390.37	464.82	74.45	462.04	–	–
5560	3.0	24,000	45.54	390.37	466.48	76.11	460.93	45.11	390.37	464.82	74.45	461.48	–	–
4893	3.0	24,000	45.51	390.37	466.48	76.11	460.93	45.07	390.37	464.82	74.45	461.48	–	–
4448	3.0	24,000	45.48	390.37	466.48	76.11	460.93	45.01	390.37	464.82	74.45	461.48	73.22-73.55	(0.33)
4204	3.0	24,000	45.46	390.37	466.48	76.11	460.93	45.06	390.37	464.82	74.45	461.48	–	–
3736	3.0	24,000	44.46	390.37	461.48	71.11	456.48	44.42	390.37	462.59	72.22	457.59	–	–
3269	3.0	24,000	44.30	390.37	460.37	70.00	454.82	44.30	390.37	461.48	71.11	456.48	–	–
2802	3.0	24,000	44.33	389.82	460.37	70.55	454.82	44.33	389.82	460.93	71.11	455.93	–	–
2335	3.0	24,000	44.30	389.82	459.82	70.00	454.26	44.31	389.82	460.93	71.11	455.37	–	–
1868	3.0	24,000	44.27	389.26	459.26	70.00	453.71	44.27	389.26	459.82	70.56	455.37	–	–
1636	3.0	24,000	44.26	387.59	457.59	70.00	452.59	44.29	387.59	458.71	71.12	453.71	69.72-70.28	(0.56)

* Cage speed expressed as a percent of shaft rpm.

***Bearing outer-race oil inlet ΔT is measured directly by a supplementary circuit for determining thermal stability.

TABLE XVIII
TASK III SKID STUDY
SOLID-BALL BEARING
240° OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN52575 S/N 2560A-2					NO. 1 BEARING (FRONT) P/N SKN52575 S/N 2560A-1						
(1) Thrust Load (lb)	(2) DN x 10^6	(3) Shaft Speed (rpm)	(4) Cage Speed Percent*	(5) Oil Inlet Temp (°F)	(6) Avg. Outer Race Temp (°F)	(7) Outer Race Oil Inlet ΔT (°F)	(8) Avg. Oil Outlet Temp (°F)	(9) Cage Speed Percent*	(10) Oil Inlet Temp (°F)	(11) Avg. Outer Race Temp (°F)	(12) Outer Race Oil Inlet ΔT (°F)	(13) Avg. Oil Outlet Temp (°F)	(14) Outer Race - Oil Inlet Measured ΔT** (°F)	(15) Variation For A 5 Minute Time Period
5000	2.8	22,400	46.34	242	376	134	363	45.56	242	369	127	363	125.6 - 126.9	(1.3)
4000	2.8	22,400	46.29	242	374	132	362	45.50	242	369	127	363	–	–
3500	2.8	22,400	46.25	242	373	131	361	45.45	242	367	125	362	–	–
3000	2.8	22,400	46.15	242	371	129	360	45.40	242	367	125	360	–	–
2500	2.8	22,400	46.19	241	370	129	359	45.41	241	366	125	360	–	–
2000	2.8	22,400	45.98	241	368	127	358	45.34	241	364	123	358	–	–
1750	2.8	22,400	45.85	240	366	126	356	45.28	240	363	123	357	–	–
1500	2.8	22,400	45.64	239	363	124	353	45.22	239	362	123	355	–	–
1250	2.8	22,400	45.29	239	360	121	350	45.10	239	359	120	353	–	–
1100	2.8	22,400	45.26	239	360	121	349	45.08	239	360	121	353	–	–
1000	2.8	22,400	45.09	239	358	119	348	45.04	239	358	119	352	117.8 - 118.5	(0.7)
945	2.8	22,400	44.94	239	357	118	348	44.92	239	357	118	351	–	–
840	2.8	22,400	44.86	238	356	118	347	44.89	238	356	118	351	–	–
735	2.8	22,400	44.80	239	357	118	348	44.83	239	357	118	351	–	–
630	2.8	22,400	44.69	239	356	117	347	44.69	239	357	118	350	–	–
525	2.8	22,400	44.36	240	352	112	343	44.39	240	354	114	348	–	–
420	2.8	22,400	44.35	239	351	112	343	44.41	239	353	114	347	–	–
368	2.8	22,400	44.16	239	350	111	341	44.34	239	352	113	344	112.3 - 114.1	(1.8)
5000	3.0	24,000	46.00	243	385	142	374	45.36	243	383	140	376	136.1 - 137.5	(1.4)
4000	3.0	24,000	45.95	243	385	142	374	45.29	243	381	138	375	–	–
3500	3.0	24,000	45.86	243	384	141	373	45.21	243	379	136	374	–	–
3000	3.0	24,000	45.80	243	384	141	372	45.21	243	380	137	373	–	–
2500	3.0	24,000	45.77	243	383	140	372	45.18	243	379	136	373	–	–
2000	3.0	24,000	45.74	243	382	139	372	45.14	243	379	136	373	–	–
1750	3.0	24,000	45.74	243	382	139	371	45.19	243	378	135	372	–	–
1500	3.0	24,000	45.69	243	382	139	372	45.19	243	377	134	372	–	–
1250	3.0	24,000	45.54	243	380	137	370	45.11	243	377	134	371	–	–
1100	3.0	24,000	45.51	243	380	137	370	45.07	243	377	134	371	–	–
1000	3.0	24,000	45.48	243	380	137	370	45.01	243	377	134	371	131.8 - 132.4	(0.6)
945	3.0	24,000	45.46	243	380	137	370	45.06	243	377	134	371	–	–
840	3.0	24,000	44.46	243	371	128	362	44.42	243	373	130	364	–	–
735	3.0	24,000	44.30	243	369	126	359	44.30	243	371	128	362	–	–
630	3.0	24,000	44.33	242	369	127	359	44.33	242	370	128	361	–	–
525	3.0	24,000	44.30	242	368	126	358	44.31	242	370	128	360	–	–
420	3.0	24,000	44.27	241	367	126	357	44.27	241	368	127	360	–	–
368	3.0	24,000	44.26	238	364	126	355	44.29	238	366	128	357	125.5 - 126.5	(1.0)

* Cage speed is expressed as percent of shaft rpm.
** Bearing outer-race oil inlet ΔT is measured directly by a supplementary circuit for determining thermal stability.

Three tests at 3.0 million DN are summarized in Tables IX to XII. Test results were similar to those at 2.8 million DN, with cage speed reductions of 1.42 and 2.29 percent for the front and rear bearings during the initial load reduction cycle. The biggest change of 0.56 percent for the front bearing and 1.00 percent for the rear bearing occurred in the small load-change from 5,560 newtons (1,250 lb) to 4,893 newtons (1,100 lb). The largest temperature changes also occurred at this time. Rig noise again became shrill and did not cease until after the bearing thrust load was increased above 13,344 newtons (3000 lb).

The results of the two additional load reduction cycles at 3.0 million DN were similar to the initial cycle. However, the biggest cage speed changes for both bearings occurred in the small load-changes from 2,335 newtons (525 lb) to 1,868 newtons (420 lb) in the first repeat test and from 3,736 newtons (840 lb) to 3,269 newtons (735 lb) in the second repeat test. The largest temperature changes, although small, coincided with the initiation of shrill noise generation when both bearings experienced the biggest change in cage speeds.

Skid-Mapping Tests at 388.7°K Oil Supply Temperatures

The results of the skid-mapping test series at an oil supply temperature of 388.7°K (240°F) were similar to those obtained during the series at 366.5°K (200°F). Bearing cage speeds did not change significantly during thrust-load reduction cycles for speeds through 2.0 million DN. Cage speeds decreased to a greater degree at 2.4 million DN at 388.7°K (240°F) than at 366.5°K (200°F) but without any corresponding significant temperature changes or noise alteration. At 2.8 million DN and 3.0 million DN, cage speeds changed significantly and were accompanied by larger temperature changes.

The test results at 2.8 million DN and 388.7°K (240°F), as shown in Tables XVII and XVIII, were almost identical to those obtained in the test at the same speed with 366.5°K (200°F) but without the change in rig noise emission.

The results for 3.0 million DN with 388.7°K (240°F) oil supply temperature, presented in Tables XVII and XVIII, were similar to those at the same DN level at 366.5°K (200°F). However, the biggest cage speed changes for both bearings occurred in the small load-readjustment from 4,204 newtons (945 lb) to 3,736 newtons (840 lb). At this time the largest temperature changes occurred and the rig noise generation again became shrill and did not cease until after the bearing thrust load was increased above 13,344 newtons (3000 lb).

Comparison of 366.5°K and 388.7°K Data

A comparison of the solid-ball bearing skid-mapping test data obtained at the two oil-inlet temperatures has indicated that the bearings are insensitive to skidding up to 2.4 million DN (19,200 rpm) at both oil supply temperatures. The bearings appear to begin skidding at 2.8 million DN (22,400 rpm) at both oil supply temperatures, as evidenced by reduction in cage speed, temperature, and the change in rig noise. Although these cage speed reductions are considered significant, they were not the large reductions that were anticipated based on experience with other solid-ball bearings at 1.0 to 1.5 million DN. The solid-ball

bearings appear to become more sensitive to skidding at 3.0 million DN (24,000 rpm) regardless of oil-inlet temperature. Relatively larger reductions in cage speed occurred at 3.0 million DN, generally at higher thrust loads, and were accompanied by larger temperature changes and a shrill noise. However, the greatest changes in cage speed did not occur at the same thrust load in the four tests performed at 3.0 million DN with the two oil supply temperatures. These results indicate a rather unstable operating regime between 5,560 newtons (1250 lb) and 1,868 newtons (420 lb) at 3.0 million DN.

A tabulation of the thermal equilibrium data for the solid-ball bearing skid mapping tests is included in columns 14 and 15 of Tables V through XVIII. It is readily apparent that the difference between outer-race and oil-in temperatures (ΔT) changed 1.1°K (2°F) or less during a five minute period of stable operation at the maximum thrust load setting for each DN speed condition. Thermal equilibrium was checked at other combinations of thrust load and DN values during the skid-mapping tests and those results are presented in the same tables.

Each solid-ball bearing accumulated 24.10 hours running time during the Task III skid-mapping tests. The running time for each bearing at each set of operating conditions is presented in Table XIX.

TABLE XIX

TASK III SOLID-BALL BEARING RUNNING TIME

P/N SKN52575 S/N 2560A-1 AND 2560A-2

Oil Inlet Temperature °K (°F)	1.0×10^6 DN (8000 rpm) hr	1.5×10^6 DN (12000 rpm) hr	2.0×10^6 DN (16000 rpm) hr	2.4×10^6 DN (19,200 rpm) hr	2.8×10^6 DN (22,400 rpm) hr	3.0×10^6 DN (24,000 rpm) hr	Startup/ Shutdown hr	Total* Bearing Time - hr
366.5 (200)	1.80	1.52	1.30	1.10	2.86	4.52	2.84	15.94
388.7 (240)	1.52	1.28	1.23	1.27	1.18	1.05	0.63	8.16
								24.10

*The bearing running time listed is the same for each test bearing.

Post-Test Inspection of Solid-Ball Bearings

The two solid-ball bearings are shown in their post test condition in Figures 16 and 17 . Generally, the inner rings, outer rings, cages, and balls of both bearings were in good condition. Ball tracks were evident on the outer-race and the load-carrying inner-race contact surfaces. These rings were a very light straw color. The nonload carrying inner-race did not contain any ball tracks and retained its original color. The land surfaces on the shoulders of both inner-ring configurations contained light circumferential rubbing contact marks from the cage rails.

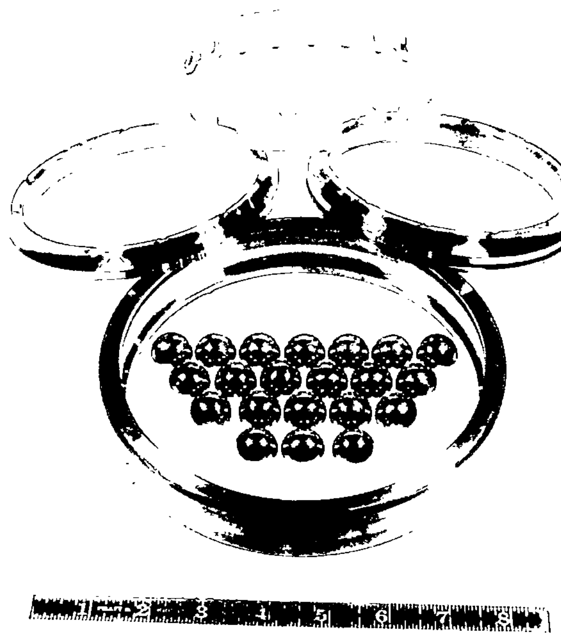


Figure 16 Overall View of Solid-Ball Bearing S/N 2560A-1 After Testing

Figure 17 Overall View of Solid-Ball Bearing S/N 2560A-2 After Testing

The appearance of typical cage surfaces is shown in Figure 18. Ball pocket contact was slightly greater in the cage rotational direction than in the axial direction; however, pocket wear was not excessive. The silver plating in the cage bore along the rail locations of the of the two bearings was lightly polished through contact with the land surfaces of the inner rings. As shown in Table XX, a negligible change was noted in the balance of the rear solid-ball bearing cage. A post-test balance check of the front bearing cage was not made.

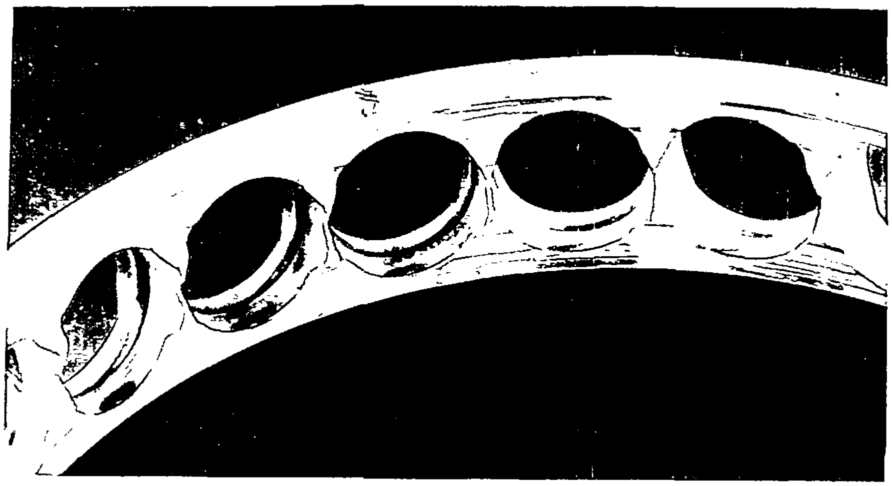


Figure 18 Appearance of Typical Cage Surfaces – Solid-Ball Bearing S/N 2560A-1

TABLE XX

SOLID-BALL AND DRILLED-BALL CAGE
UNBALANCE MEASUREMENTS

	Pretest (gm-cm)	Post-Test (gm-cm)
Task III Solid-Ball Run		
2560A-1 (Front)	1.5	
2560A-2 (Rear)	2.0	2.0
Task III Drilled-Ball Run		
2600A-1 (Front)	1.0	1.0
2600A-2 (Rear)	1.0	-
2552A-2 (Rear)	1.5	2.0
Task IV Cyclic Endurance		
2560A-1 (Front)		2.5
2552A-2 (Rear)	2.0	2.0

Typical ball surface appearances are shown in Figure 19. The balls from both bearings did contain some orbital markings, but they were generally in good condition and retained their original color. Neither set of solid balls contained any evidence of ball skidding.

Figure 19 Appearance of Typical Solid Balls - Solid-Ball Bearing S/N 2560A-1

DRILLED-BALL BEARING TESTS

Two drilled-ball bearings (S/N 2600 A-1 and S/N 2600 A-2) completed skid-mapping tests through 2.8 million DN at 366.5°K (200°F) oil supply temperature. Only one thrust-load reduction cycle was run at each DN level with bearing thrust loads generally ranging from 22,241 newtons (5000 lb) to approximately 1,779 newtons (400 lb).

Skid testing of the two drilled-ball bearings was discontinued at 366.5°K (200°F) following the 2.8 million DN test because unusual intermittent noise generation occurred within the test rig as the shaft speed was being increased to 3.0 million DN (24,000 rpm). This occurred at approximately 2.9 million DN but without any increase in rig vibration or unusual bearing outer ring temperatures. The test rig was shutdown immediately and inspection revealed that the cage of the rear bearing (S/N 2600 A-2) had slightly more axial freedom than the front bearing. At high speeds, this cage moved axially with thrust load adjustments, overlapped the end of the bearing inner ring, and lightly contacted an adjacent spacer ring. The rub was limited circumferentially and did not penetrate the copper flashing under the cage's silver plating which was one to two mils thick. It was found that the ball pocket diameter of this cage was five mils larger than that of the three other drilled-ball cages which allowed the cage more axial travel. The adjacent spacer rings were reworked to prevent further contact and the test rig was reassembled with the same drilled-ball bearings for further skid-mapping tests.

At 2.8 million DN and low thrust loads, the cage speed of the rear drilled-ball bearing was somewhat higher than that of the front bearing and did not continue to decrease when the bearing thrust load was reduced from 4,448 newtons (1000 lb) to 1,636 newtons (368 lb). This suggested that the cage was being driven by intermittent contact with the spacer ring under those load conditions. Therefore, it was planned to repeat the skid-mapping test at 2.8 million DN.

During restart of the test rig, drilled-ball bearing performances were normal up to 2.8 million DN. However, the test rig was shutdown to correct a test stand problem before the skid-mapping test could be started at 2.8 million DN. Testing subsequently was suspended at 2.62 million DN following a second restart when the outer ring temperature of the rear bearing (S/N 2600 A-2) suddenly exceeded 533.15°K (500°F) and the bearing collapsed. Extensive damage was sustained by the various components of the rear bearing including eleven broken balls.

Since the possibility existed that the drilled balls might be overloaded at a thrust load of 22,241 newtons (5000 lb), the maximum thrust load was reduced to 13,344 newtons (3000 lb) for further drilled-ball bearing tests at 388.7°K (240°F) oil supply temperature

Skid-mapping tests at 388.7°K (240°F) were then initiated with bearing S/N 2600 A-1 and S/N 2552 A-2 and were completed through 2.8 million DN. One thrust-load reduction cycle was run at each DN level. Bearing thrust loads generally ranged from 13,344 newtons (3000 lb) to approximately 1,779 newtons (400 lb) at each DN level up to 2.4 million DN. Thrust loads only ranged from 13,344 newtons (3000 lb) to 8,896 newtons (2000 lb) at 2.8 million DN because of a sudden large decrease in cage speed at 8,896 newtons (2000 lb).

An attempt was then made to increase shaft speed for further testing at 3.0 million DN. This was discontinued when the shaft speed reached 2.9 million DN and rig vibration increased substantially. Inspection revealed that one drilled-ball had fractured into two principal pieces which had wedged themselves in the cage ball pocket. A small splinter-like segment had been ejected from the bearing.

Drilled-Ball Bearing Performance

Cage speed and temperature data for the drilled-ball bearings are summarized in Tables XXI through XXXIV. Tables XXI through XXVIII provide the data for the test series with bearings S/N 2600 A-1 and S/N 2600 A-2 at an oil supply temperature of 366.5°K (200°F), and Tables XXIX through XXXIV provide the data for bearings S/N 2600 A-1 and S/N 2552 A-2 at an oil supply temperature of 388.7°K (240°F).

Skid-Mapping Tests at 366.5°K Oil Supply Temperature

Bearing cage speeds did not change significantly during thrust-load reduction cycles for all speeds through 2.0 million DN at 366.5°K (200°F) oil supply temperature, as shown in Tables XXI through XXIV. Cage speeds did change significantly at 2.4 million DN and 2.8 million DN.

TABLE XXI
TASK III SKID STUDY
DRILLED-BALL BEARING
366.5°K OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN52576 S/N 2600A-2					NO. 1 BEARING (FRONT) P/N SKN52576 S/N 2600A-1						
(1) Thrust Load (newtons)	(2) DN x 10^6	(3) Shaft Speed (rpm)	(4) Cage Speed Percent*	(5) Oil Inlet Temp (°K)	(6) Avg. Outer Race Temp (°K)	(7) Outer Race Oil Inlet ΔT (°K)	(8) Avg. Oil Outlet Temp (°K)	(9) Cage Speed Percent*	(10) Oil Inlet Temp (°K)	(11) Avg. Outer Race Temp (°K)	(12) Outer Race Oil Inlet ΔT (°K)	(13) Avg. Oil Outlet Temp (°K)	(14) Outer Race - Oil Inlet Measured ΔT** (°K) Variation For 5 Minute Time Period	(15)
22241	1.0	8,000	44.71	366.48	384.26	17.78	382.04	44.64	366.48	384.26	17.78	379.82	17.72 - 17.94	(0.22)
17793	1.0	8,000	44.79	367.04	384.82	17.78	382.04	44.68	367.04	384.26	17.22	379.82	–	–
13344	1.0	8,000	44.46	366.48	383.15	16.67	380.37	44.36	366.48	382.59	16.11	378.71	–	–
11121	1.0	8,000	44.54	367.04	383.15	16.11	379.82	44.43	367.04	382.59	15.55	378.71	–	–
8896	1.0	8,000	44.64	367.04	382.04	15.00	379.26	44.43	367.04	382.04	15.00	378.15	–	–
7784	1.0	8,000	44.61	367.04	382.04	15.00	378.71	44.32	367.04	382.04	15.00	377.59	–	–
6672	1.0	8,000	44.54	367.04	381.48	14.44	378.71	44.36	367.04	381.48	14.44	377.59	–	–
6072	1.0	8,000	44.50	367.04	381.48	14.44	378.71	44.36	367.04	381.48	14.44	377.59	–	–
5560	1.0	8,000	44.54	367.59	382.04	14.45	378.71	44.39	367.59	382.04	14.45	378.15	–	–
5138	1.0	8,000	44.50	367.59	381.48	13.89	378.15	44.39	367.59	381.48	13.89	377.59	–	–
4893	1.0	8,000	44.54	366.48	381.48	15.00	377.59	44.39	366.48	381.48	15.00	377.59	–	–
4448	1.0	8,000	44.54	366.48	381.48	15.00	377.59	44.39	366.48	381.48	15.00	377.59	15.00 - 15.11	(0.11)
4204	1.0	8,000	44.54	365.93	380.93	15.00	377.59	44.39	365.93	380.93	15.00	376.48	–	–
3736	1.0	8,000	44.57	365.93	380.93	15.00	377.04	44.43	365.93	380.93	15.00	376.48	–	–
3269	1.0	8,000	44.57	365.93	380.93	15.00	377.04	44.43	365.93	380.93	15.00	376.48	–	–
2802	1.0	8,000	44.50	366.48	380.93	14.45	377.04	44.36	366.48	380.93	14.45	376.48	–	–
2335	1.0	8,000	44.46	366.48	380.93	14.45	377.59	44.32	366.48	380.93	14.45	376.48	14.88 - 15.05	(0.17)
1868	1.0	8,000	44.50	367.04	381.48	14.44	377.04	44.32	367.04	381.48	14.44	377.04	–	–
1636	1.0	8,000	44.50	366.48	380.93	14.45	377.04	44.36	366.48	380.93	14.45	377.04	–	–
22241	1.5	12,000	44.95	367.04	400.37	33.33	398.15	44.79	367.04	395.37	28.33	389.82	29.16 - 29.72	(0.56)
17793	1.5	12,000	45.02	366.48	399.82	33.34	397.04	44.86	366.48	394.82	28.34	389.26	–	–
13344	1.5	12,000	45.02	366.48	399.26	32.78	395.93	44.83	366.48	393.71	27.23	388.71	–	–
11121	1.5	12,000	45.07	366.48	396.48	30.00	392.59	44.86	366.48	390.93	24.45	387.04	–	–
8896	1.5	12,000	45.05	365.93	394.82	28.89	390.37	44.83	365.93	389.82	23.89	385.37	–	–
7784	1.5	12,000	45.00	365.93	394.82	28.89	390.37	44.81	365.93	389.26	23.33	384.82	–	–
6672	1.5	12,000	45.02	365.93	394.82	28.89	390.37	44.81	365.93	389.26	23.33	385.37	–	–
6072	1.5	12,000	45.02	365.93	394.82	28.89	389.82	44.81	365.93	389.26	23.33	385.37	–	–
5560	1.5	12,000	45.07	365.93	394.26	28.33	389.26	44.86	365.93	389.26	23.33	385.37	–	–
5138	1.5	12,000	45.05	365.93	394.26	28.33	389.26	44.83	365.93	389.26	23.33	384.82	–	–
4893	1.5	12,000	45.05	365.93	394.26	28.33	388.15	44.81	365.93	389.26	23.33	384.82	–	–
4448	1.5	12,000	45.10	367.04	394.82	27.78	390.37	44.88	367.04	389.82	22.78	385.37	23.61 - 23.88	(0.27)
4204	1.5	12,000	45.05	367.59	394.82	27.23	389.82	44.83	367.59	389.82	22.23	385.93	–	–
3736	1.5	12,000	45.05	367.59	394.82	27.23	389.26	44.81	367.59	389.82	22.23	385.93	–	–
3269	1.5	12,000	45.10	367.59	394.26	26.67	388.71	44.86	367.59	389.26	21.67	385.37	–	–
2802	1.5	12,000	45.12	367.59	393.71	26.12	388.71	44.86	367.59	389.26	21.67	385.37	–	–
2335	1.5	12,000	45.10	366.48	392.59	26.11	387.04	44.83	366.48	388.15	21.67	384.26	22.38 - 22.94	(0.56)
1868	1.5	12,000	45.10	367.59	393.15	25.56	388.15	44.83	367.59	388.71	21.12	384.82	–	–
1636	1.5	12,000	45.10	367.59	393.15	25.56	388.15	44.81	367.59	388.71	21.12	384.82	–	–

* Cage speed expressed as a percent of shaft rpm.
** Bearing outer-race oil inlet ΔT is measured by a supplementary circuit for determining thermal stability.

TABLE XXII
TASK III SKID STUDY
DRILLED-BALL BEARING
200°F OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN52576 S/N 2600A-2					NO. 1 BEARING (FRONT) P/N SKN52576 S/N 2600A-1						
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Thrust Load (lb)	DN x 10^6	Shaft Speed (rpm)	Cage Speed Percent*	Oil Inlet Temp (°F)	Avg. Outer Race Temp (°F)	Outer Race Oil Inlet ΔT (°F)	Avg. Oil Outlet Temp (°F)	Cage Speed Percent*	Oil Inlet Temp (°F)	Avg. Outer Race Temp (°F)	Outer Race Oil Inlet ΔT (°F)	Avg. Oil Outlet Temp (°F)	Outer Race - Oil Inlet Measured ΔT** (°F)	Variation For a 5 Minute Time Period
5000	1.0	8,000	44.71	200	232	32	228	44.64	200	232	32	224	31.9 - 32.7	(0.8)
4000	1.0	8,000	44.79	201	233	32	228	44.68	201	232	31	224	–	–
3000	1.0	8,000	44.46	200	230	30	225	44.36	200	229	29	222	–	–
2500	1.0	8,000	44.54	201	230	29	224	44.43	201	229	28	222	–	–
2000	1.0	8,000	44.64	201	228	27	223	44.43	201	228	27	221	–	–
1750	1.0	8,000	44.61	201	228	27	222	44.32	201	228	27	220	–	–
1500	1.0	8,000	44.54	201	227	26	222	44.36	201	227	26	220	–	–
1365	1.0	8,000	44.50	201	227	26	222	44.36	201	227	26	220	–	–
1250	1.0	8,000	44.54	202	228	26	222	44.39	202	228	26	221	–	–
1155	1.0	8,000	44.50	202	227	27	221	44.39	202	227	27	220	–	–
1100	1.0	8,000	44.54	200	227	27	220	44.39	200	227	27	220	–	–
1000	1.0	8,000	44.54	200	227	27	220	44.39	200	227	27	220	27.0 - 27.2	(0.2)
945	1.0	8,000	44.54	199	226	27	220	44.39	199	226	27	218	–	–
840	1.0	8,000	44.57	199	226	27	219	44.43	199	226	27	218	–	–
735	1.0	8,000	44.57	199	226	27	219	44.43	199	226	27	218	–	–
630	1.0	8,000	44.50	200	226	26	219	44.36	200	226	26	218	–	–
525	1.0	8,000	44.46	200	226	26	220	44.32	200	226	26	218	26.8 - 27.1	(0.3)
420	1.0	8,000	44.50	201	227	26	219	44.32	201	227	26	219	–	–
368	1.0	8,000	44.50	200	226	26	219	44.36	200	226	26	219	–	–
5000	1.5	12,000	44.95	201	261	60	257	44.79	201	252	51	242	52.5 - 53.5	(1.0)
4000	1.5	12,000	45.02	200	260	60	255	44.86	200	251	51	241	–	–
3000	1.5	12,000	45.02	200	259	59	253	44.83	200	249	49	240	–	–
2500	1.5	12,000	45.07	200	254	54	247	44.86	200	244	44	237	–	–
2000	1.5	12,000	45.05	199	251	52	243	44.83	199	242	43	234	–	–
1750	1.5	12,000	45.00	199	251	52	243	44.81	199	241	42	233	–	–
1500	1.5	12,000	45.02	199	251	52	243	44.81	199	241	42	234	–	–
1365	1.5	12,000	45.02	199	251	52	242	44.81	199	241	42	234	–	–
1250	1.5	12,000	45.07	199	250	51	241	44.86	199	241	42	234	–	–
1155	1.5	12,000	45.05	199	250	51	241	44.83	199	241	42	233	–	–
1100	1.5	12,000	45.05	199	250	51	239	44.81	199	241	42	233	–	–
1000	1.5	12,000	45.10	201	251	50	243	44.88	201	242	41	234	42.5 - 43.0	(0.5)
945	1.5	12,000	45.05	202	251	49	242	44.83	202	242	40	235	–	–
840	1.5	12,000	45.05	202	251	49	241	44.81	202	242	40	235	–	–
735	1.5	12,000	45.10	202	250	48	240	44.86	202	241	39	234	–	–
630	1.5	12,000	45.12	202	249	47	240	44.86	202	241	39	234	–	–
525	1.5	12,000	45.10	200	247	47	237	44.83	200	239	39	232	40.3 - 41.3	(1.0)
420	1.5	12,000	45.10	202	248	46	239	44.83	202	240	38	233	–	–
368	1.5	12,000	45.10	202	248	46	239	44.81	202	240	38	233	–	–

* Cage speed is expressed as percent of shaft rpm.

** Bearing outer-race oil inlet ΔT is measured directly by a supplementary circuit for determining thermal stability.

TABLE XXIII
TASK III SKID STUDY
DRILLED-BALL BEARING
366.5°K OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN52576 S/N 2600A-2					NO. 1 BEARING (FRONT) P/N SKN52576 S/N 2600A-1						
(1) Thrust Load (newtons)	(2) DN x 10^6	(3) Shaft Speed (rpm)	(4) Cage Speed Percent*	(5) Oil Inlet Temp (°K)	(6) Avg. Outer Race Temp (°K)	(7) Outer Race Oil Inlet ΔT (°K)	(8) Avg. Oil Outlet Temp (°K)	(9) Cage Speed Percent*	(10) Oil Inlet Temp (°K)	(11) Avg. Outer Race Temp (°K)	(12) Outer Race Oil Inlet ΔT (°K)	(13) Avg. Oil Outlet Temp (°K)	(14) Outer Race - Oil Inlet Measured ΔT** (°K) Variation For a 5 Minute Time Period	(15)
22241	2.0	16,000	45.18	366.48	415.37	48.89	407.59	44.84	366.48	406.48	40.00	400.37	40.83 - 41.66	(0.83)
17793	2.0	16,000	45.16	366.48	414.82	48.34	407.59	44.82	366.48	405.93	39.45	400.37	–	–
13344	2.0	16,000	45.20	366.48	412.04	45.56	405.37	44.84	366.48	403.71	37.23	398.71	–	–
11121	2.0	16,000	45.23	366.48	410.37	43.89	404.26	44.82	366.48	402.04	35.56	398.15	–	–
8896	2.0	16,000	45.32	366.48	409.26	42.78	403.15	44.91	366.48	401.48	35.00	397.04	–	–
7784	2.0	16,000	45.32	366.48	408.71	42.23	403.15	44.91	366.48	401.48	35.00	397.04	–	–
6672	2.0	16,000	45.32	366.48	408.15	41.67	402.59	44.89	366.48	400.37	33.89	397.04	–	–
6072	2.0	16,000	45.30	366.48	408.15	41.67	402.04	44.86	366.48	400.37	33.89	397.04	–	–
5560	2.0	16,000	45.29	366.48	408.15	41.67	402.04	44.84	366.48	400.37	33.89	397.04	–	–
5138	2.0	16,000	45.27	366.48	408.15	41.67	402.59	44.82	366.48	400.37	33.89	397.04	–	–
4893	2.0	16,000	45.18	366.48	407.04	40.56	401.48	44.70	366.48	399.26	32.78	395.37	–	–
4448	2.0	16,000	45.23	366.48	406.48	40.00	400.93	44.75	366.48	398.71	32.23	394.82	34.11 - 34.22	(0.11)
4204	2.0	16,000	45.29	365.93	406.48	40.55	400.93	44.79	365.93	398.71	32.78	394.82	–	–
3736	2.0	16,000	45.29	366.48	406.48	40.00	400.93	44.80	366.48	399.26	32.78	395.37	–	–
3269	2.0	16,000	45.29	365.93	405.93	40.00	400.93	44.79	365.93	398.71	32.78	394.82	–	–
2802	2.0	16,000	45.30	366.48	405.93	39.45	400.93	44.79	366.48	398.71	32.23	394.82	–	–
2335	2.0	16,000	45.34	366.48	405.93	39.45	400.37	44.89	366.48	398.71	32.23	394.82	33.88 - 34.05	(0.17)
1868	2.0	16,000	45.34	367.59	407.04	39.45	401.48	44.80	367.59	399.82	32.23	395.37	–	–
1636	2.0	16,000	45.32	367.59	407.04	39.45	401.48	44.80	367.59	399.82	32.23	396.48	–	–
22241	2.4	19,200	45.73	366.48	424.82	58.34	418.15	45.16	366.48	414.26	47.78	412.04	49.00 - 49.72	(0.72)
17793	2.4	19,200	45.62	367.59	423.16	55.57	417.04	45.07	367.59	414.26	46.67	410.93	–	–
13344	2.4	19,200	45.68	367.59	423.16	55.57	416.48	45.09	367.59	414.26	46.67	410.93	–	–
11121	2.4	19,200	45.62	367.59	422.59	55.00	415.93	45.06	367.59	413.71	46.12	410.93	–	–
8896	2.4	19,200	45.61	367.59	420.93	53.34	415.37	44.99	367.59	412.59	45.00	409.26	–	–
7784	2.4	19,200	45.62	367.59	420.93	53.34	414.82	45.00	367.59	412.59	45.00	409.82	–	–
6672	2.4	19,200	45.52	367.59	420.37	52.78	414.82	44.85	367.59	412.04	44.45	409.82	–	–
6072	2.4	19,200	45.48	367.59	420.37	52.78	414.26	44.85	367.59	412.04	44.45	409.26	–	–
5560	2.4	19,200	45.51	367.04	419.82	52.78	414.26	44.85	367.04	411.48	44.44	408.71	–	–
5138	2.4	19,200	45.49	367.59	419.82	52.23	414.26	44.84	367.59	411.48	43.89	408.71	–	–
4893	2.4	19,200	45.49	367.59	419.82	52.23	414.26	44.85	367.59	411.48	43.89	408.71	–	–
4448	2.4	19,200	45.21	366.48	416.48	50.00	411.48	44.42	366.48	408.71	42.23	405.93	44.16 - 44.44	(0.28)
4204	2.4	19,200	45.19	365.93	415.93	50.00	410.93	44.39	365.93	408.15	42.22	405.37	–	–
3736	2.4	19,200	44.88	365.37	415.37	50.00	410.93	44.15	365.37	408.15	42.78	404.82	–	–
3269	2.4	19,200	44.91	365.37	414.82	49.45	410.37	44.21	365.37	408.15	42.78	404.26	–	–
2802	2.4	19,200	44.97	365.37	414.82	49.45	410.37	44.26	365.37	407.59	42.22	404.82	–	–
2335	2.4	19,200	44.82	366.48	414.82	48.34	410.37	44.15	366.48	408.15	41.67	404.26	43.50 - 44.16	(0.66)
1868	2.4	19,200	44.72	366.48	414.82	48.34	409.82	44.09	366.48	408.15	41.67	404.82	–	–
1636	2.4	19,200	44.72	365.93	414.26	48.33	409.26	44.08	365.93	407.59	41.66	404.26	–	–

* Cage speed expressed as a percent of shaft rpm.
** Bearing outer-race oil inlet ΔT is measured directly by a supplementary circuit for determining thermal stability.

TABLE XXIV
TASK III SKID STUDY
DRILLED-BALL BEARING
200°F OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN52576 S/N 2600A-2					NO. 1 BEARING (FRONT) P/N SKN52576 S/N 2600A-1						
(1) Thrust Load (lb)	(2) DN x 10^6	(3) Shaft Speed (rpm)	(4) Cage Speed Percent*	(5) Oil Inlet Temp (°F)	(6) Avg. Outer Race Temp (°F)	(7) Outer Race Oil Inlet ΔT (°F)	(8) Avg. Oil Outlet Temp (°F)	(9) Cage Speed Percent*	(10) Oil Inlet Temp (°F)	(11) Avg. Outer Race Temp (°F)	(12) Outer Race Oil Inlet ΔT (°F)	(13) Avg. Oil Outlet Temp (°F)	(14) Outer Race - Oil Inlet Measured ΔT (°F)**	(15) ΔT Variation For a 5 Minute Time Period
5000	2.0	16,000	45.18	200	288	88	274	44.84	200	272	72	261	73.6 - 75.0	(1.5)
4000	2.0	16,000	45.16	200	287	87	274	44.82	200	271	71	261	–	–
3000	2.0	16,000	45.20	200	282	82	270	44.84	200	267	67	258	–	–
2500	2.0	16,000	45.23	200	279	79	268	44.82	200	264	64	257	–	–
2000	2.0	16,000	45.32	200	277	77	266	44.91	200	263	63	255	–	–
1750	2.0	16,000	45.32	200	276	76	266	44.91	200	263	63	254	–	–
1500	2.0	16,000	45.32	200	275	75	265	44.89	200	261	61	254	–	–
1365	2.0	16,000	45.30	200	275	75	264	44.86	200	261	61	254	–	–
1250	2.0	16,000	45.29	200	275	75	264	44.84	200	261	61	254	–	–
1155	2.0	16,000	45.27	200	275	75	265	44.82	200	261	61	254	–	–
1100	2.0	16,000	45.18	200	273	73	263	44.70	200	259	59	252	–	–
1000	2.0	16,000	45.23	200	272	72	262	44.75	200	258	58	251	61.4 - 61.6	(0.2)
945	2.0	16,000	45.29	199	272	73	262	44.79	199	258	59	251	–	–
840	2.0	16,000	45.29	200	272	72	262	44.80	200	259	59	252	–	–
735	2.0	16,000	45.29	199	271	72	262	44.79	199	258	59	251	–	–
630	2.0	16,000	45.30	200	271	71	262	44.79	200	258	58	251	–	–
525	2.0	16,000	45.34	200	271	71	261	44.89	200	258	58	251	61.0 - 61.3	(0.3)
420	2.0	16,000	45.34	202	273	71	263	44.80	202	260	58	252	–	–
368	2.0	16,000	45.32	202	273	71	263	44.80	202	260	58	254	–	–
5000	2.4	19,200	45.73	200	305	105	293	45.16	200	286	86	282	88.2 - 89.5	(1.3)
4000	2.4	19,200	45.62	202	302	100	291	45.07	202	286	84	280	–	–
3000	2.4	19,200	45.68	202	302	100	290	45.09	202	286	84	280	–	–
2500	2.4	19,200	45.62	202	301	99	289	45.06	202	285	83	280	–	–
2000	2.4	19,200	45.61	202	298	96	288	44.99	202	283	81	277	–	–
1750	2.4	19,200	45.62	202	298	96	287	45.00	202	283	81	278	–	–
1500	2.4	19,200	45.52	202	297	95	287	44.85	202	282	80	278	–	–
1365	2.4	19,200	45.48	202	297	95	286	44.85	202	282	80	277	–	–
1250	2.4	19,200	45.51	201	296	95	286	44.85	201	281	80	276	–	–
1155	2.4	19,200	45.49	202	296	94	286	44.84	202	281	79	276	–	–
1100	2.4	19,200	45.49	202	296	94	286	44.85	202	281	79	276	–	–
1000	2.4	19,200	45.21	200	290	90	281	44.42	200	276	76	271	79.5 - 80.0	(0.5)
945	2.4	19,200	45.19	199	289	90	280	44.39	199	275	76	270	–	–
840	2.4	19,200	44.88	198	288	90	280	44.15	198	275	77	269	–	–
735	2.4	19,200	44.91	198	287	89	279	44.21	198	275	77	268	–	–
630	2.4	19,200	44.97	198	287	89	279	44.26	198	274	76	269	–	–
525	2.4	19,200	44.82	200	287	87	279	44.15	200	275	75	268	78.3 - 79.5	(1.2)
420	2.4	19,200	44.72	200	287	87	278	44.09	200	275	75	269	–	–
368	2.4	19,200	44.72	199	286	87	277	44.08	199	274	75	268	–	–

* Cage speed is expressed as percent of shaft rpm.

** Bearing outer-race oil inlet ΔT is measured directly by a supplementary circuit for determining thermal stability.

TABLE XXV
TASK III SKID STUDY
DRILLED-BALL BEARING
366.5°K OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN 52576 S/N 2600A-2					No. 1 BEARING (FRONT) P/N SKN52576 S/N 2600A-1						
(1) Thrust Load (newtons)	(2) DN x 10^6	(3) Shaft Speed (rpm)	(4) Cage Speed Percent*	(5) Oil Inlet Temp (°K)	(6) Avg. Outer Race Temp (°K)	(7) Outer Race Oil Inlet ΔT (°K)	(8) Avg. Oil Outlet Temp (°K)	(9) Cage Speed Percent*	(10) Oil Inlet Temp (°K)	(11) Avg. Outer Race Temp (°K)	(12) Outer Race Oil Inlet ΔT (°K)	(13) Avg. Oil Outlet Temp (°K)	(14) Outer Race - Oil Inlet Measured ΔT** (°K) Variation For a 5 Minute Time Period	(15)
22241	2.8	22,400	46.06	367.04	438.15	71.11	432.04	45.08	367.04	427.59	60.55	423.71	61.22 - 61.83	(0.61)
17793	2.8	22,400	46.05	366.48	438.71	72.23	432.04	45.04	366.48	427.59	61.11	424.26	–	–
13344	2.8	22,400	45.41	367.04	435.37	68.33	428.71	44.59	367.04	426.48	59.44	423.71	–	–
11121	2.8	22,400	45.28	366.48	431.48	65.00	427.04	44.52	366.48	424.82	58.34	420.93	–	–
8896	2.8	22,400	45.19	367.04	431.48	64.44	426.48	44.49	367.04	424.82	57.78	420.93	–	–
7784	2.8	22,400	45.26	366.48	431.48	65.00	425.93	44.52	366.48	424.82	58.34	420.93	–	–
6672	2.8	22,400	45.20	366.48	430.93	64.45	426.48	44.50	366.48	424.82	68.34	420.37	–	–
6072	2.8	22,400	45.27	366.48	430.93	64.45	425.93	44.52	366.48	424.26	57.78	420.37	–	–
5560	2.8	22,400	45.27	365.93	430.37	64.44	425.93	44.50	365.93	423.71	57.78	420.37	–	–
5138	2.8	22,400	45.24	366.48	430.37	63.89	425.37	44.50	366.48	423.71	57.23	420.37	–	–
4893	2.8	22,400	45.22	366.48	429.82	63.34	425.37	44.48	366.48	423.15	56.67	419.26	–	–
4448	2.8	22,400	45.05	366.48	429.82	63.34	424.82	44.25	366.48	423.15	56.67	419.82	58.11 - 58.38	(0.27)
4204	2.8	22,400	45.05	366.48	429.82	63.34	424.82	44.26	366.48	423.15	56.67	419.82	–	–
3736	2.8	22,400	45.04	366.48	429.82	63.34	424.82	44.21	366.48	423.15	56.67	419.82	–	–
3269	2.8	22,400	45.04	366.48	429.82	63.34	424.82	44.23	366.48	423.15	56.67	419.26	–	–
2802	2.8	22,400	45.04	366.48	429.82	63.34	424.82	44.34	366.48	423.15	56.67	419.26	–	–
2335	2.8	22,400	44.96	366.48	429.26	62.78	424.82	44.16	366.48	422.59	56.11	418.71	57.61 - 58.22	(0.61)
1868	2.8	22,400	44.96	366.48	429.26	62.78	424.26	44.16	366.48	422.59	56.11	418.71	–	–
1636	2.8	22,400	44.96	366.48	429.26	62.78	424.82	44.15	366.48	422.59	56.11	418.71	–	–

* Cage speed expressed as a percent of shaft rpm.

** Bearing outer-race oil inlet ΔT is measured directly by a supplementary circuit for determining thermal stability.

TABLE XXVI
TASK III SKID STUDY
DRILLED BALL BEARING
200°F OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR P/N SKN52576 S/N 2600A-2					NO. 1 BEARING (FRONT) P/N SKN52576 S/N 2600A-1						
(1) Thrust Load (lb)	(2) DN x 10^6	(3) Shaft Speed (rpm)	(4) Cage Speed Percent*	(5) Oil Inlet Temp (°F)	(6) Avg. Outer Race Temp (°F)	(7) Outer Race Oil Inlet ΔT (°F)	(8) Avg. Oil Outlet Temp (°F)	(9) Cage Speed Percent*	(10) Oil Inlet Temp (°F)	(11) Avg. Outer Race Temp (°F)	(12) Outer Race Oil Inlet ΔT (°F)	(13) Avg. Oil Outlet Temp (°F)	(14) Outer Race - Oil Inlet Measured ΔT**(°F) Variation For A 5 Minute Time Period	(15)
5000	2.8	22,400	46.06	201	329	128	318	45.08	201	310	109	303	110.2 - 111.3	(1.1)
4000	2.8	22,400	46.05	200	330	130	318	45.04	200	310	110	304	–	–
3000	2.8	22,400	45.41	201	324	123	312	44.59	201	308	107	303	–	–
2500	2.8	22,400	45.28	200	317	117	309	44.52	200	305	105	298	–	–
2000	2.8	22,400	45.19	201	317	116	308	44.49	201	305	104	298	–	–
1750	2.8	22,400	45.26	200	317	117	307	44.52	200	305	105	298	–	–
1500	2.8	22,400	45.20	200	316	116	308	44.50	200	305	105	297	–	–
1365	2.8	22,400	45.27	200	316	116	307	44.52	200	304	104	297	–	–
1250	2.8	22,400	45.27	199	315	116	307	44.50	199	303	104	297	–	–
1155	2.8	22,400	45.24	200	315	115	306	44.50	200	303	103	297	–	–
1100	2.8	22,400	45.22	200	314	114	306	44.48	200	302	102	295	–	–
1000	2.8	22,400	45.05	200	314	114	305	44.25	200	302	102	296	104.6 - 105.1	(0.5)
945	2.8	22,400	45.05	200	314	114	305	44.26	200	302	102	296	–	–
840	2.8	22,400	45.04	200	314	114	305	44.21	200	302	102	296	–	–
735	2.8	22,400	45.04	200	314	114	305	44.23	200	302	102	295	–	–
630	2.8	22,400	45.04	200	314	114	305	44.34	200	302	102	295	–	–
525	2.8	22,400	44.96	200	313	113	305	44.16	200	301	101	294	103.7 - 104.8	(1.1)
420	2.8	22,400	44.96	200	313	113	304	44.16	200	301	101	294	–	–
368	2.8	22,400	44.96	200	313	113	305	44.15	200	301	101	294	–	–

* Cage speed is expressed as percent of shaft rpm.

** Bearing outer-race oil inlet ΔT is measured directly by a supplementary circuit for determining thermal stability.

TABLE XXVII
TASK III SKID STUDY
DRILLED-BALL BEARING
(FIRST FAILURE)
366.5°K OIL INLET TEMPERATURE

(1)	(2)	(3)	NO. 2 BEARING (REAR) P/N SKN 52576 S/N 2600A-2 (4)	(5)	(6)	(7)	(8)	NO. 1 BEARING (FRONT) P/N SKN 52576 S/N 2600A-1 (9)	(10)	(11)	(12)	(13)
Thrust Load (newtons)	DN x 10^6	Shaft Speed (rpm)	Cage Speed Percent*	Oil Inlet Temp (°K)	Avg. Outer Race Temp (°K)	Outer Race Oil Inlet ΔT (°K)	Avg. Oil Outlet Temp (°K)	Cage Speed Percent*	Oil Inlet Temp (°K)	Avg. Outer Race Temp (°K)	Outer Race Oil Inlet ΔT (°K)	Avg. Oil Outlet Temp (°K)
22241	1.0	8,000	44.93	366.48	384.26	17.78	379.26	44.82	366.48	384.26	17.78	379.26
22241	1.5	12,000	46.07	363.71	392.04	28.33	385.93	45.88	363.71	389.26	25.55	384.82
22241	2.0	16,000	46.32	364.82	407.04	42.22	402.04	46.20	364.82	403.15	38.33	398.71
22241	2.4	19,200	46.19	365.93	420.93	55.00	412.59	45.88	365.93	416.48	50.55	411.48
22241	2.6	21,000	46.45	366.48	426.48	60.00	420.37	45.99	366.48	423.71	57.23	419.82
22241	2.6	21,000	45.74	365.37	425.93	60.56	420.93	45.28	365.37	422.04	56.67	418.71
22241	2.6	21,000	45.77	364.82	425.93	61.11	420.37	45.29	364.82	421.48	56.66	418.15
13344	2.6	21,000	45.81	364.82	424.82	60.00	419.82	45.31	364.82	420.37	55.55	417.04
13344	2.8	22,400	45.46	364.82	429.82	65.00	424.26	44.91	364.82	426.48	61.66	423.16
13344	1.0	8,000	45.11	364.82	379.26	14.44	375.37	44.96	364.82	379.26	14.44	374.26
22241	1.0	8,000	44.75	364.26	383.71	19.45	376.48	-----	364.26	383.71	19.45	377.59
22241	1.5	12,000	45.38	364.82	396.48	31.66	387.04	45.62	364.82	394.82	30.00	388.71
22241	2.0	16,000	45.20	365.37	409.82	44.45	399.82	45.05	365.37	408.15	42.78	400.93
22241	2.4	19,200	45.85	363.71	422.04	58.33	413.15	45.67	363.71	420.93	57.22	414.82
22241	2.8	22,400	-----	367.59	466.48	98.89	439.82	-----	367.59	433.15	65.56	428.15
22241	2.6	21,000	46.05	364.82	449.26	84.44	433.71	45.99	364.82	427.04	62.22	423.71

*Cage speed expressed as a percent of shaft rpm.

TABLE XXVIII
TASK III SKID STUDY
DRILLED-BALL BEARING
FIRST FAILURE
200°F OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN 52576 S/N 2600A-2					NO. 1 BEARING (FRONT) P/N SKN 52576 S/N 2600A-1				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Thrust Load (lb)	DN x 10^6	Shaft Speed (rpm)	Cage Speed Percent*	Oil Inlet Temp (°F)	Avg. Outer Race Temp (°F)	Outer Race Oil Inlet ΔT (°F)	Avg. Oil Outlet Temp (°F)	Cage Speed Percent*	Oil Inlet Temp (°F)	Avg. Outer Race Temp (°F)	Outer Race Oil Inlet ΔT (°F)	Avg. Oil Outlet Temp (°F)
5000	1.0	8,000	44.93	200	232	32	223	44.82	200	232	32	223
5000	1.5	12,000	46.07	195	246	51	235	45.88	195	241	46	233
5000	2.0	16,000	46.32	197	273	76	264	46.20	197	266	69	258
5000	2.4	19,200	46.19	199	298	99	283	45.88	199	290	91	281
5000	2.6	21,000	46.45	200	308	108	297	45.99	200	303	103	296
5000	2.6	21,000	45.74	198	307	109	298	45.28	198	300	102	294
5000	2.6	21,000	45.77	197	307	110	297	45.29	197	299	102	293
3000	2.6	21,000	45.81	197	305	108	296	45.31	197	297	100	291
3000	2.8	22,400	45.46	197	314	117	304	44.91	197	308	111	302
3000	1.0	8,000	45.11	197	223	27	216	44.96	197	223	27	214
5000	1.0	8,000	44.75	196	231	34	218	.....	196	231	34	220
5000	1.5	12,000	45.38	197	254	56	237	45.62	197	251	53	240
5000	2.0	16,000	45.20	198	278	83	260	45.05	198	275	80	262
5000	2.4	19,200	45.85	195	300	103	284	45.67	195	298	101	287
5000	2.8	22,400	.....	202	380	178	332	.....	202	320	118	311
5000	2.6	21,000	46.05	197	349	146	321	45.99	197	309	106	303

*Cage speed expressed as a percent of shaft rpm.

TABLE XXIX
TASK III SKID STUDY
DRILLED-BALL BEARING
388.7°K OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN52576 S/N 2552A-2					NO. 1 BEARING (FRONT) P/N SKN52576 S/N2600A-1						
(1) Thrust Load (newtons)	(2) DN x 10^6	(3) Shaft Speed (rpm)	(4) Cage Speed Percent*	(5) Oil Inlet Temp (°K)	(6) Avg. Outer Race Temp (°K)	(7) Outer Race Oil Inlet ΔT (°K)	(8) Avg. Oil Outlet Temp (°K)	(9) Cage Speed Percent*	(10) Oil Inlet Temp (°K)	(11) Avg. Outer Race Temp (°K)	(12) Outer Race Oil Inlet ΔT (°K)	(13) Avg. Oil Outlet Temp (°K)	(14) Outer Race - Oil Inlet Measured ΔT** (°K)	(15) Variation for a 5 Minute Time Period
13344	1.0	8,000	44.50	388.71	400.37	11.66	397.04	44.50	388.71	400.37	11.66	397.04	11.83 - 12.05	(0.22)
11121	1.0	8,000	44.39	389.26	400.93	11.67	397.59	44.32	389.26	400.93	11.67	397.59	–	–
8896	1.0	8,000	44.54	389.26	400.93	11.67	397.59	44.50	389.26	400.93	11.67	397.59	–	–
7784	1.0	8,000	44.57	387.04	399.26	12.22	396.48	44.54	387.04	399.26	12.22	396.48	–	–
6672	1.0	8,000	44.61	387.04	398.71	11.67	395.37	44.57	387.04	398.71	11.67	395.93	–	–
6072	1.0	8,000	44.61	387.04	398.71	11.67	395.93	44.61	387.04	398.71	11.67	395.93	–	–
5560	1.0	8,000	44.32	388.15	399.82	11.67	396.48	44.29	388.15	399.82	11.67	396.48	–	–
5138	1.0	8,000	44.36	388.15	399.82	11.67	396.48	44.32	388.15	399.82	11.67	396.48	–	–
4893	1.0	8,000	44.36	388.71	400.37	11.66	397.04	44.32	388.71	400.37	11.66	397.04	–	–
4448	1.0	8,000	44.39	389.26	400.93	11.67	397.59	44.36	389.26	400.93	11.67	397.59	11.50 - 11.77	(0.27)
4204	1.0	8,000	44.43	388.71	400.93	12.22	398.15	44.39	388.71	400.93	12.22	397.59	–	–
3736	1.0	8,000	44.39	388.71	400.93	12.22	398.15	44.36	388.71	400.93	12.22	397.59	–	–
3269	1.0	8,000	44.50	387.04	398.71	11.67	395.93	44.50	387.04	398.71	11.67	395.93	–	–
2802	1.0	8,000	44.46	387.04	398.71	11.67	395.93	44.46	387.04	398.71	11.67	395.93	–	–
2335	1.0	8,000	44.50	387.04	398.71	11.67	395.37	44.50	387.04	398.71	11.67	395.37	–	–
1868	1.0	8,000	44.54	387.59	399.82	12.23	395.93	44.54	387.59	399.82	12.23	395.93	11.83 - 12.00	(0.17)
1636	1.0	8,000	44.54	388.15	399.82	11.67	396.48	44.54	388.15	399.82	11.67	396.48	–	–
13344	1.5	12,000	44.95	388.15	409.26	21.11	405.93	44.88	388.15	407.04	18.89	404.26	18.88 - 19.16	(0.28)
11121	1.5	12,000	44.93	388.15	409.26	21.11	405.93	44.88	388.15	407.04	18.89	404.82	–	–
8896	1.5	12,000	44.86	388.15	409.26	21.11	405.37	44.79	388.15	407.04	18.89	404.82	–	–
7784	1.5	12,000	44.93	388.15	409.26	21.11	405.93	44.83	388.15	407.04	18.89	404.82	–	–
6672	1.5	12,000	44.86	388.15	409.26	21.11	405.37	44.79	388.15	407.04	18.89	404.82	–	–
6072	1.5	12,000	44.95	388.15	409.26	21.11	405.93	44.88	388.15	407.04	18.89	404.82	–	–
5560	1.5	12,000	44.90	388.15	409.26	21.11	405.37	44.83	388.15	407.59	19.44	404.82	–	–
5138	1.5	12,000	44.93	388.15	409.26	21.11	405.37	44.83	388.15	407.04	18.89	404.82	–	–
4893	1.5	12,000	44.86	388.15	408.71	20.56	405.37	44.79	388.15	407.04	18.89	404.82	–	–
4448	1.5	12,000	44.88	388.15	408.71	20.56	405.37	44.81	388.15	407.04	18.89	404.82	19.00 - 19.16	(0.16)
4204	1.5	12,000	44.93	388.15	408.71	20.56	405.37	44.86	388.15	406.48	18.33	404.82	–	–
3736	1.5	12,000	44.90	388.15	408.71	20.56	405.37	44.81	388.15	407.04	18.89	404.26	–	–
3269	1.5	12,000	44.93	388.71	408.71	20.00	405.37	44.86	388.71	407.04	18.33	404.82	–	–
2802	1.5	12,000	44.88	388.71	409.26	20.55	405.93	44.81	388.71	407.04	18.33	404.82	–	–
2335	1.5	12,000	44.88	388.71	409.26	20.55	405.93	44.79	388.71	409.59	20.88	405.37	–	–
1868	1.5	12,000	44.86	389.26	409.82	20.56	405.93	44.76	389.26	409.59	20.33	405.37	18.77 - 19.00	(0.23)
1636	1.5	12,000	44.88	389.26	409.26	20.00	405.37	44.83	389.26	409.59	20.33	405.37	–	–

* Cage speed expressed as a percent of shaft rpm.
**Bearing outer-race oil inlet ΔT is measured directly by a supplementary circuit for determining thermal stability.

TABLE XXX
TASK III SKID STUDY
DRILLED-BALL BEARING
240°F OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN52576 S/N 2552A-2					NO. 1 BEARING (FRONT) P/N SKN52576 S/N 2600A-1						
(1) Thrust Load (lb)	(2) DN x 10^6	(3) Shaft Speed (rpm)	(4) Cage Speed Percent*	(5) Oil Inlet Temp (°F)	(6) Avg. Outer Race Temp (°F)	(7) Outer Race Oil Inlet ΔT (°F)	(8) Avg. Oil Outlet Temp (°F)	(9) Cage Speed Percent *	(10) Oil Inlet Temp (°F)	(11) Avg. Outer Race Temp (°F)	(12) Outer Race Oil Inlet ΔT (°F)	(13) Avg. Oil Outlet Temp (°F)	(14) Outer Race - Oil Inlet Measured ΔT** (°F)	(15) Variation For a 5 Minute Time Period
3000	1.0	8,000	44.50	240	261	21	255	44.50	240	261	21	255	21.3 - 21.7	(0.4)
2500	1.0	8,000	44.39	241	262	21	256	44.32	241	262	21	256	–	–
2000	1.0	8,000	44.54	241	262	21	256	44.50	241	262	21	256	–	–
1750	1.0	8,000	44.57	237	259	22	254	44.54	237	259	22	254	–	–
1500	1.0	8,000	44.61	237	258	21	252	44.57	237	258	21	253	–	–
1365	1.0	8,000	44.61	237	258	21	253	44.61	237	258	21	253	–	–
1250	1.0	8,000	44.32	239	260	21	254	44.29	239	260	21	254	–	–
1155	1.0	8,000	44.36	239	260	21	254	44.32	239	260	21	254	–	–
1100	1.0	8,000	44.36	240	261	21	255	44.32	240	261	21	255	–	–
1000	1.0	8,000	44.39	241	262	21	256	44.36	241	262	21	256	20.7 - 21.2	(0.5)
945	1.0	8,000	44.43	240	262	22	257	44.39	240	262	22	256	–	–
840	1.0	8,000	44.39	240	262	22	257	44.36	240	262	22	256	–	–
735	1.0	8,000	44.50	237	258	21	253	44.50	237	258	21	253	–	–
630	1.0	8,000	44.46	237	258	21	253	44.46	237	258	21	253	–	–
525	1.0	8,000	44.50	237	258	21	252	44.50	237	258	21	252	–	–
420	1.0	8,000	44.54	238	260	22	253	44.54	238	259	21	253	21.3 - 21.6	(0.3)
368	1.0	8,000	44.54	239	260	21	254	44.54	239	260	21	255	–	–
3000	1.5	12,000	44.95	239	277	38	271	44.88	239	273	34	268	34.0 - 34.5	(0.5)
2500	1.5	12,000	44.93	239	277	38	271	44.88	239	273	34	269	–	–
2000	1.5	12,000	44.86	239	277	38	270	44.79	239	273	34	269	–	–
1750	1.5	12,000	44.93	239	277	38	271	44.83	239	273	34	269	–	–
1500	1.5	12,000	44.86	239	277	38	270	44.79	239	273	34	269	–	–
1365	1.5	12,000	44.95	239	277	38	271	44.88	239	273	34	269	–	–
1250	1.5	12,000	44.90	239	277	38	270	44.83	239	274	35	269	–	–
1155	1.5	12,000	44.93	239	277	38	270	44.83	239	273	34	269	–	–
1100	1.5	12,000	44.86	239	276	37	270	44.79	239	273	34	269	–	–
1000	1.5	12,000	44.88	239	276	37	270	44.81	239	273	34	269	34.2 - 34.5	(0.3)
945	1.5	12,000	44.93	239	276	37	270	44.86	239	272	33	269	–	–
840	1.5	12,000	44.90	239	276	37	270	44.81	239	273	34	268	–	–
735	1.5	12,000	44.93	240	276	36	270	44.86	240	273	33	269	–	–
630	1.5	12,000	44.88	240	277	37	271	44.81	240	273	33	269	–	–
525	1.5	12,000	44.88	240	277	•37	271	44.79	240	274	34	270	–	–
420	1.5	12,000	44.86	241	278	37	271	44.76	241	274	33	270	33.8 - 34.2	(0.4)
368	1.5	12,000	44.88	241	277	38	270	44.83	241	274	33	270	–	–

* Cage speed is expressed as percent of shaft rpm.

**Bearing outer-race oil inlet ΔT is measured directly by a supplementary circuit for determining thermal stability.

TABLE XXXI
TASK III SKID STUDY
DRILLED BALL BEARING
388.5°K OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN52576 S/N 2552A-2					NO. 1 BEARING (FRONT) P/N SKN52576 S/N 2600A-1						
(1) Thrust Load (newtons)	(2) DN x 10^6	(3) Shaft Speed (rpm)	(4) Cage Speed Percent*	(5) Oil Inlet Temp (°K)	(6) Avg. Outer Race Temp (°K)	(7) Outer Race Oil Inlet ΔT (°K)	(8) Avg. Oil Outlet Temp (°K)	(9) Cage Speed Percent*	(10) Oil Inlet Temp (°K)	(11) Avg. Outer Race Temp (°K)	(12) Outer Race Oil Inlet ΔT (°K)	(13) Avg. Oil Outlet Temp (°K)	(14) Outer Race - Oil Inlet Measured ΔT** (°K) Variation for A 5 Minute Time Period	(15)
13344	2.0	16,000	44.93	388.15	420.93	32.78	414.26	44.77	388.15	418.15	30.00	415.37	30.83 - 31.05	(0.22)
11121	2.0	16,000	44.89	388.15	420.93	32.78	414.26	44.73	388.15	418.15	30.00	415.37	–	–
8896	2.0	16,000	44.91	388.71	421.48	32.77	414.82	44.73	388.71	418.71	30.00	415.37	–	–
7784	2.0	16,000	44.80	388.71	421.48	32.77	414.82	44.64	388.71	418.71	30.00	415.37	–	–
6672	2.0	16,000	44.86	388.15	420.93	32.78	414.82	44.70	388.15	418.15	30.00	415.37	–	–
6072	2.0	16,000	44.82	388.15	420.93	32.78	415.93	44.66	388.15	418.15	30.00	415.37	–	–
5560	2.0	16,000	44.86	388.71	420.93	32.22	414.82	44.66	388.71	418.15	29.44	415.37	–	–
5138	2.0	16,000	44.86	388.71	420.93	32.22	414.82	44.68	388.71	418.15	29.44	415.37	–	–
4893	2.0	16,000	44.82	387.04	420.93	33.89	414.82	44.64	387.04	418.15	31.11	415.37	–	–
4448	2.0	16,000	44.75	388.15	420.93	32.78	414.82	44.61	388.15	418.15	30.00	415.93	30.11 - 30.55	(0.44)
4204	2.0	16,000	44.71	390.37	422.59	32.22	416.48	44.55	390.37	419.82	29.45	417.04	–	–
3736	2.0	16,000	44.73	388.71	422.93	34.22	415.37	44.57	388.71	418.15	29.44	415.93	–	–
3269	2.0	16,000	44.71	388.71	422.93	34.22	414.82	44.55	388.71	418.15	29.44	415.93	–	–
2802	2.0	16,000	44.64	387.59	419.82	32.23	414.26	44.46	387.59	417.59	30.00	414.82	–	–
2335	2.0	16,000	44.71	389.82	421.48	31.66	415.37	44.55	389.82	418.71	28.89	416.48	–	–
1868	2.0	16,000	44.68	389.26	422.04	32.78	415.93	44.55	389.26	419.26	30.00	417.04	29.83 - 30.55	(0.72)
1636	2.0	16,000	44.70	388.71	421.48	32.77	414.82	44.54	388.71	418.15	29.44	415.93	–	–
13344	2.4	19,200	44.73	389.26	435.37	46.11	428.15	44.43	389.26	430.93	41.67	428.15	42.33 - 42.88	(0.55)
11121	2.4	19,200	44.58	389.82	435.93	46.11	428.71	44.26	389.82	431.48	41.66	428.71	–	–
8896	2.4	19,200	44.52	390.37	436.48	46.11	429.26	44.20	390.37	432.04	41.67	420.26	–	–
7784	2.4	19,200	44.42	387.59	432.59	45.00	426.48	44.11	387.59	428.71	41.12	425.93	–	–
6672	2.4	19,200	44.45	387.59	433.15	45.56	425.93	44.15	387.59	428.71	41.12	425.93	–	–
6072	2.4	19,200	44.43	388.71	434.26	45.55	426.48	44.17	388.71	429.26	40.55	427.04	–	–
5560	2.4	19,200	44.51	389.26	434.82	45.56	428.15	44.21	389.26	430.37	41.11	428.15	–	–
5138	2.4	19,200	44.36	388.15	433.71	45.56	427.04	44.03	388.15	429.26	41.11	427.04	–	–
4893	2.4	19,200	44.29	388.71	433.71	45.00	427.59	44.00	388.71	429.82	41.11	427.04	–	–
4448	2.4	19,200	44.42	388.71	434.82	46.11	427.59	44.12	388.71	429.82	41.11	427.59	41.77 - 42.27	(0.50)
4204	2.4	19,200	44.45	388.15	433.71	45.56	427.04	44.18	388.15	429.26	41.11	427.04	–	–
3736	2.4	19,200	44.46	389.82	435.37	45.55	528.15	44.18	389.82	430.93	41.11	428.15	–	–
3269	2.4	19,200	44.45	388.15	433.71	45.56	427.04	44.20	388.15	429.82	41.67	427.04	–	–
2802	2.4	19,200	44.40	388.71	433.71	45.00	427.59	44.12	388.71	429.82	41.11	427.59	–	–
2335	2.4	19,200	44.40	390.37	435.93	43.56	428.71	44.11	390.37	430.93	40.59	428.15	–	–
1868	2.4	19,200	44.40	388.15	433.15	45.00	427.04	44.14	388.15	429.26	41.11	427.04	–	–

* Cage speed expressed as a percent of shaft rpm.
**Bearing outer-race oil inlet ΔT is measured directly by a supplementary circuit for determining thermal stability.

TABLE XXXII
TASK III SKID STUDY
DRILLED-BALL BEARING
240°F OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN52576 S/N 2552A-2					NO. 1 BEARING (FRONT) P/N SKN52576 S/N 2605A-1						
(1) Thrust Load (lb)	(2) DN x 10^6	(3) Shaft Speed (rpm)	(4) Cage Speed Percent*	(5) Oil Inlet Temp (°F)	(6) Avg. Outer Race Temp (°F)	(7) Outer Race Oil Inlet ΔT (°F)	(8) Avg. Oil Outlet Temp (°F)	(9) Cage Speed Percent*	(10) Oil Inlet Temp (°F)	(11) Avg. Outer Race Temp (°F)	(12) Outer Race Oil Inlet ΔT(°F)	(13) Avg. Oil Outlet Temp (°F)	(14) Outer Race - Oil Inlet Measured ΔT**(°F)	(15) Variation For a 5 Minute Time Period
3000	2.0	16,000	44.93	239	298	59	286	44.77	239	293	54	288	55.5 - 55.9	(0.4)
2500	2.0	16,000	44.89	239	298	59	286	44.73	239	293	54	288	–	–
2000	2.0	16,000	44.91	240	299	59	287	44.73	240	294	54	288	–	–
1750	2.0	16,000	44.80	240	299	59	287	44.64	240	294	54	288	–	–
1500	2.0	16,000	44.86	239	298	59	287	44.70	239	293	54	288	–	–
1365	2.0	16,000	44.82	239	298	59	289	44.66	239	293	54	288	–	–
1250	2.0	16,000	44.86	240	298	58	287	44.66	240	293	53	288	–	–
1155	2.0	16,000	44.86	240	298	58	287	44.68	240	293	53	288	–	–
1100	2.0	16,000	44.82	237	298	61	287	44.64	237	293	56	288	–	–
1000	2.0	16,000	44.75	239	298	59	287	44.61	239	293	54	289	54.2 - 55.0	(0.8)
945	2.0	16,000	44.71	243	301	58	290	44.55	243	296	53	291	–	–
840	2.0	16,000	44.73	240	298	58	288	44.57	240	293	53	289	–	–
735	2.0	16,000	44.71	240	298	58	287	44.55	240	293	53	289	–	–
630	2.0	16,000	44.64	238	296	58	286	44.46	238	292	54	287	–	–
525	2.0	16,000	44.71	242	299	57	288	44.55	242	294	52	290	–	–
420	2.0	16,000	44.68	241	300	59	289	44.55	241	295	54	291	53.7 - 55.0	(1.3)
368	2.0	16,000	44.70	240	299	59	287	44.54	240	293	53	289	–	–
3000	2.4	19,200	44.73	241	324	83	311	44.43	241	316	75	311	76.2 - 77.2	(1.0)
2500	2.4	19,200	44.58	242	325	83	312	44.26	242	317	75	312	–	–
2000	2.4	19,200	44.52	243	326	83	313	44.20	243	318	75	313	–	–
1750	2.4	19,200	44.42	238	319	81	308	44.11	238	312	74	307	–	–
1500	2.4	19,200	44.45	238	320	82	307	44.15	238	312	74	307	–	–
1365	2.4	19,200	44.43	240	322	82	308	44.17	240	313	73	309	–	–
1250	2.4	19,200	44.51	241	323	82	311	44.21	241	315	74	311	–	–
1155	2.4	19,200	44.36	239	321	82	309	44.03	239	313	74	309	–	–
1100	2.4	19,200	44.29	240	321	81	310	44.00	240	314	74	309	–	–
1000	2.4	19,200	44.42	240	323	83	310	44.12	240	314	74	310	75.2 - 76.1	(0.9)
945	2.4	19,200	44.45	239	321	82	309	44.18	239	313	74	309	–	–
840	2.4	19,200	44.46	242	324	82	311	44.18	242	316	74	311	–	–
735	2.4	19,200	44.45	239	321	82	309	44.20	239	314	75	309	–	–
630	2.4	19,200	44.40	240	321	81	310	44.12	240	314	74	310	–	–
525	2.4	19,200	44.40	243	325	82	312	44.11	243	316	73	311	–	–
420	2.4	19,200	44.40	239	320	81	309	44.14	239	313	74	309	–	–

* Cage speed is expressed as percent of shaft rpm.

** Bearing outer-race oil inlet ΔT is measured directly by a supplementary circuit for determining thermal stability.

TABLE XXXIII
TASK III SKID STUDY
DRILLED-BALL BEARING
SECOND FAILURE
388.7°K OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN52576 S/N 2552A-2					NO. 1 BEARING (FRONT) P/N SKN52576 S/N 2600A-1						
(1) Thrust Load (newtons)	(2) DN x 10^6	(3) Shaft Speed (rpm)	(4) Cage Speed Percent*	(5) Oil Inlet Temp (°K)	(6) Avg. Outer Race Temp (°K)	(7) Outer Race Oil Inlet ΔT (°K)	(8) Avg. Oil Outlet Temp (°K)	(9) Cage Speed Percent*	(10) Oil Inlet Temp (°K)	(11) Avg. Outer Race Temp (°K)	(12) Outer Race Oil Inlet ΔT (°K)	(13) Avg. Oil Outlet Temp (°K)	(14) Outer Race - Oil Inlet Measured Δ**T (°K)	(15) Variation For a 5 Minute Time Period
13344	1.0	8,000	44.75	388.71	401.48	12.77	397.59	44.68	388.71	400.93	12.22	397.59	–	–
13344	1.5	12,000	45.14	389.26	411.48	22.22	406.48	44.17	389.26	408.15	18.89	404.82	–	–
13344	2.0	16,000	45.18	387.59	422.59	35.00	415.37	45.09	387.59	418.71	31.12	414.82	–	–
13344	2.4	19,200	45.31	389.26	437.04	47.78	428.71	45.06	389.26	431.48	42.22	428.15	–	–
13344	2.8	22,400	44.95	388.15	451.48	63.33	443.15	44.54	388.15	444.26	56.11	442.59	56.38 - 57.50	(1.12)
11121	2.8	22,400	44.85	388.15	451.48	63.33	443.15	44.49	388.15	444.82	56.67	442.59	–	–
8896	2.8	22,400	44.76	387.59	448.71	61.12	442.59	44.36	387.59	444.26	56.67	442.04	–	–
8896	2.8	22,400	44.95	387.59	448.71	61.12	442.59	44.54	387.59	454.26	66.67	446.48	–	–
8896	2.8	22,400	44.62	387.59	449.26	61.67	442.59	42.41	387.59	446.48	58.89	442.59	–	–
13344	2.8	22,400	45.11	388.15	450.93	62.78	442.59	43.02	388.15	444.26	56.11	440.37	–	–
13344	2.0	16,000	45.00	387.59	421.48	33.89	415.37	42.68	387.59	418.15	30.56	415.37	–	–
13344	1.5	12,000	44.81	388.71	411.48	22.77	408.15	42.43	388.71	409.26	20.55	407.04	–	–
13344	1.0	8,000	44.29	388.71	402.59	13.88	398.71	40.64	388.71	402.59	13.88	400.37	–	–

* Cage speed expressed as a percent of shaft rpm.
** Bearing outer-race inlet ΔT is measured directly by a supplementary circuit for determining thermal stability

TABLE XXXIV
TASK III SKID STUDY
DRILLED-BALL BEARING
SECOND FAILURE
240°F OIL INLET TEMPERATURE

			NO. 2 BEARING (REAR) P/N SKN52576 S/N 2552A-2					NO. 1 BEARING (FRONT) P/N SKN52576 S/N 2600A-1						
(1) Thrust Load (lb)	(2) DN x 10^6	(3) Shaft Speed (rpm)	(4) Cage Speed Percent*	(5) Oil Inlet Temp (°F)	(6) Avg. Outer Race Temp (°F)	(7) Outer Race Oil Inlet ΔT (°F)	(8) Avg. Oil Outlet Temp (°F)	(9) Cage Speed Percent	(10) Oil Inlet Temp (°F)	(11) Avg. Outer Race Temp (°F)	(12) Outer Race Oil Inlet ΔT (°F)	(13) Avg. Oil Outlet Temp (°F)	(14) Outer Race - Oil Inlet Measured ΔT** (°F)	(15) Variation For a 5 Minute Time Period
3000	1.0	8,000	44.75	240	263	23	256	44.68	240	262	22	256	–	–
3000	1.5	12,000	45.14	241	281	40	272	44.17	241	275	34	269	–	–
3000	2.0	16,000	45.18	238	301	63	288	45.09	238	294	56	287	–	–
3000	2.4	19,200	45.31	241	327	86	312	45.06	241	317	76	311	–	–
3000	2.8	22,400	44.95	239	353	114	338	44.54	239	340	101	337	101.5-103.5	(2.0)
2500	2.8	22,400	44.85	239	353	114	339	44.49	239	341	102	337	–	–
2000	2.8	22,400	44.76	238	348	110	337	44.36	238	340	102	336	–	–
2000	2.8	22,400	44.95	238	348	110	337	44.54	238	358	120	344	–	–
2000	2.8	22,400	44.62	239	349	111	337	42.41	238	344	106	337	–	–
3000	2.8	22,400	45.11	239	352	113	337	43.02	239	340	101	333	–	–
3000	2.0	16,000	45.00	238	299	61	288	42.68	238	293	55	288	–	–
3000	1.5	12,000	44.81	240	281	41	275	42.43	240	277	37	273	–	–
3000	1.0	8,000	44.29	240	265	25	258	40.64	240	265	25	261	–	–

* Cage speed is expressed as percent of shaft rpm.
** Bearing outer-race oil inlet ΔT is measured directly by a supplementary circuit for determining thermal stability.

Test results at 2.4 million DN are summarized in Tables XXIII and XXIV. Cage speed reductions of 1.08 and 1.01 percent of shaft speed occurred for the front and rear bearings over the entire thrust-load reduction cycle. Bearing cage speeds decreased gradually throughout the load reduction cycle except for changes of 0.43 percent for the front bearing and 0.28 percent for the rear bearing in the small load-range from 4,893 newtons (1100 lb) to 4,448 newtons (1000 lb). Change of bearing differential temperatures in that range was slightly larger than for other reductions in thrust load. There was no abnormal noise generation during this skid test.

The results of the skid-mapping test at 2.8 million DN are presented in Tables XXV and XXVI. The test results were similar to those obtained at 2.4 million DN, with overall cage speed reductions of 0.93 percent for the front bearing and 1.10 percent for the rear bearing. The biggest change of 0.45 percent for the front bearing and 0.64 percent for the rear bearing occurred in the load reduction from 17,793 newtons (4000 lb) to 13,344 newtons (3000 lb). Only a slight change in rear bearing differential and oil outlet temperatures was observed. There was no sudden shift in noise generation during this test; however, the rig noise level was rather high during the entire thrust-load reduction cycle.

Testing was subsequently terminated at 2.62 million DN during a second restart when the rear bearing, S/N 2600 A-2, failed. Bearing performances were normal up to 2.4 million DN, as shown in Tables XXVII and XXVIII. Rig vibration increased suddenly while setting the shaft speed at 2.8 million DN (22,400 rpm) at 22,241 newtons (5000 lb). A reduction in shaft speed to 2.62 million DN reduced vibration to normal levels. As shown in Figure 20, cage speeds were normal at that condition, but the outer-ring temperature of the rear bearing was 448.7°K (348°F) as compared to 427°K (309°F) for the front bearing. Rig vibration peaked again after approximately three minutes at 2.62 million DN and the rear bearing outer-ring temperature exceeded 533.15°K (500°F) in less than thirty seconds. At this time the test rig automatically shut down because of increased torque loading on the electric drive motor.

Inspection revealed that eleven of twenty-one balls had broken in the rear bearing, causing it to collapse. The cage was intact, and all of the ball restraining pins were firmly in place. The front bearing, S/N 2600 A-1, was found to be in good condition. Detailed inspection results are presented in the Post-Test Inspection of Drilled-Ball Bearings section.

Skid-Mapping Tests at 388.7°K Oil Supply Temperature

Tests results from the skid-mapping test series at an oil supply temperature of 388.7°K (240°F) differed slightly from those obtained at 366.5°K (200°F). Bearing cage speeds did not change significantly during the thrust-load reduction cycles for all speeds through 2.4 million DN, as shown in Tables XXIX through XXXII. Cage speed and temperatures of the front bearing, S/N 2600 A-1, did change significantly at 2.8 million DN, as shown in Figure 21.

Bearing performance was normal during the entire startup procedure up to 2.8 million DN, as shown in Tables XXXIII and XXXIV. Cage speeds and temperatures of both bearings remained normal during stabilization at 2.8 million DN and during the thrust-load reduction from 13,344 newtons (3000 lb) to 8,896 newtons (2000 lb), as shown in Figure 21. After

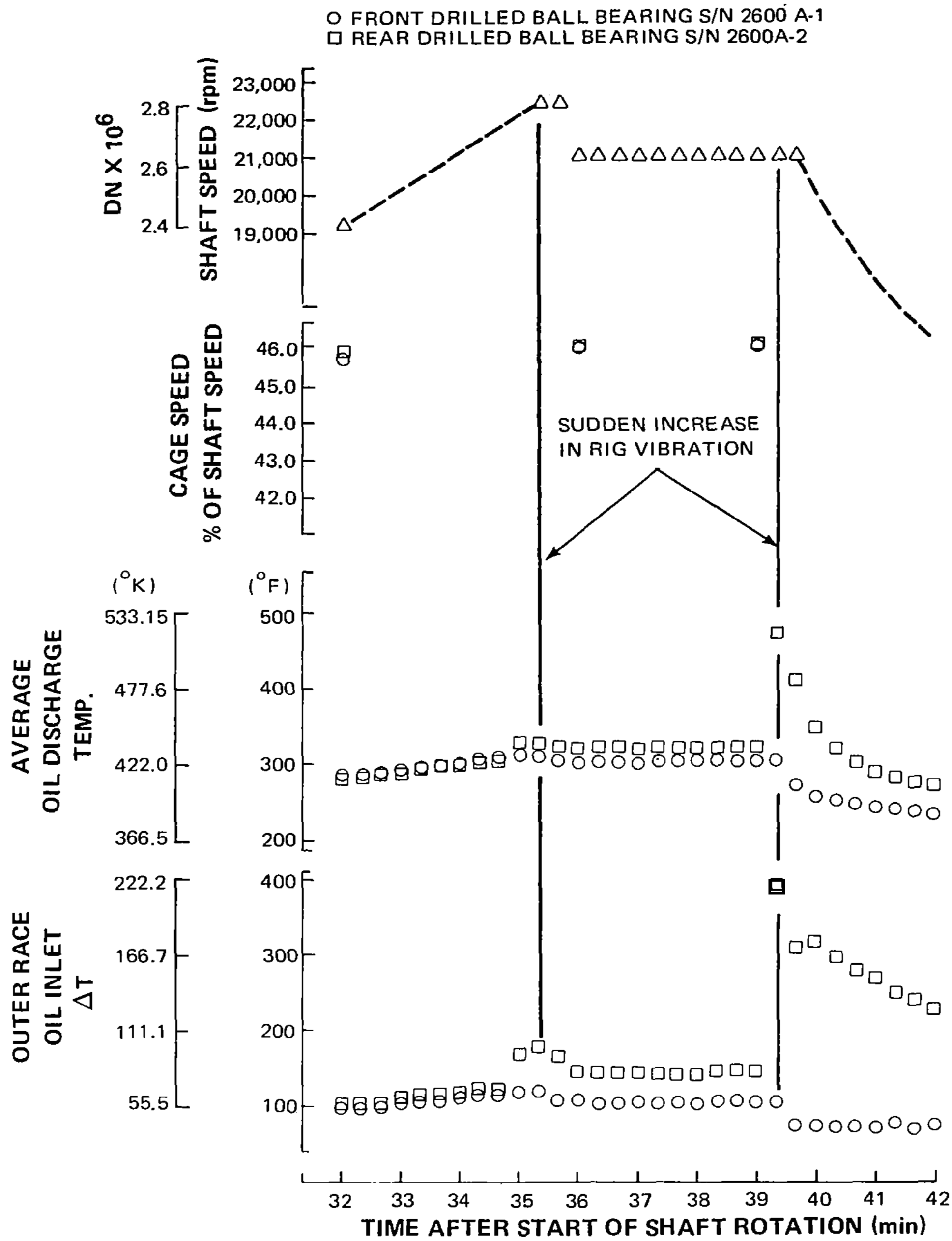


Figure 20 Drilled-Ball Bearing Failure (S/N 2600A-2) at 2.8 Million DN (22,400 rpm)
Task III Drill-Ball Bearing Skid-Mapping Test
Thrust Load = 22241 N (5000 lb)/Bearing
Oil Inlet Temperature = 366.5°K ± 1.7° (200°F ± 3°)
Bearing Lubrication = 121 X 10^{-3} kg/sec (16 lb/min)/Bearing

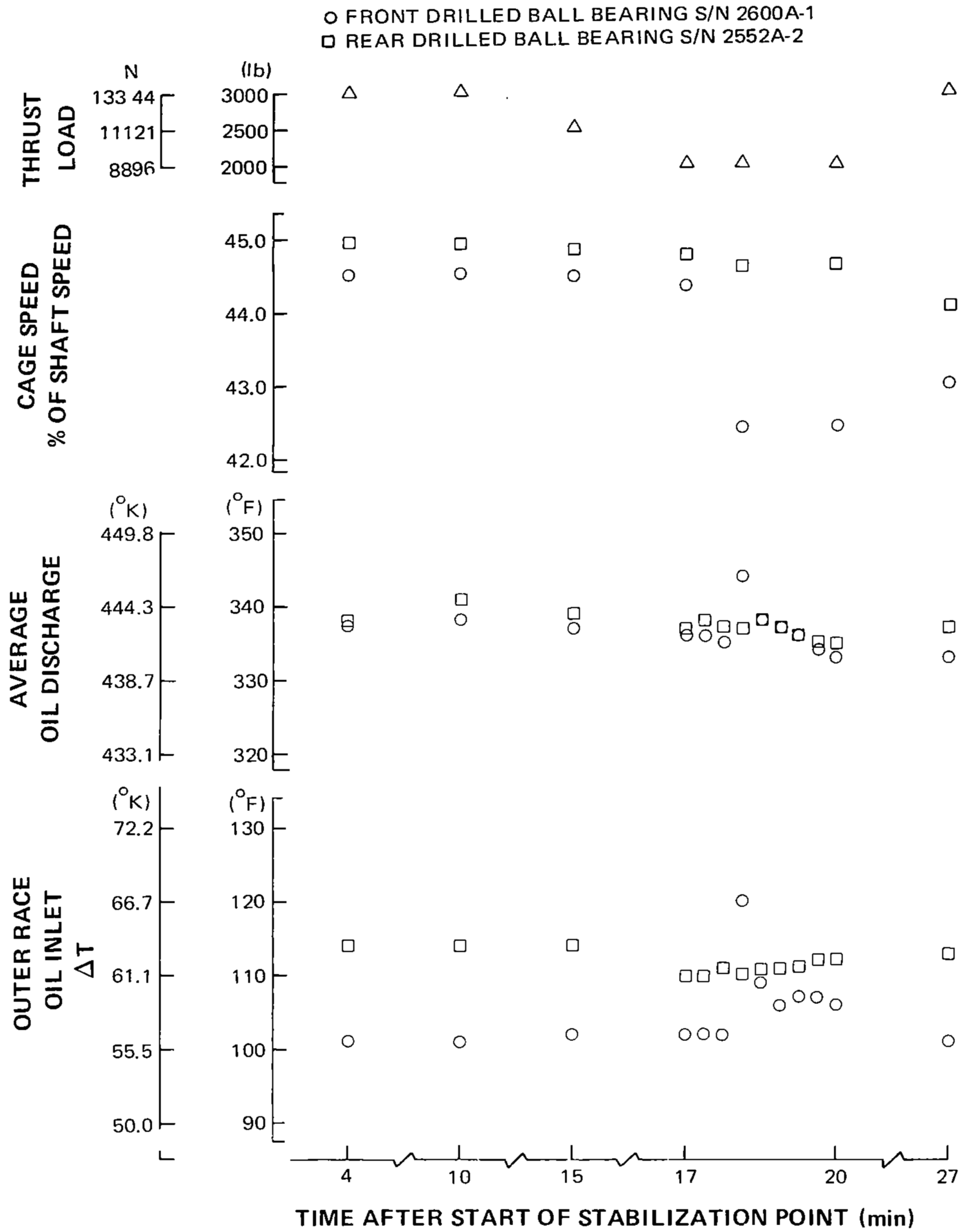


Figure 21 Drilled-Ball Bearing (S/N 2600A-1) at 2.8 Million DN (22,400 rpm)
Task III Drilled-Ball Bearing Skid-Mapping Test

Shaft Speed = 2.8 Million DN (22,400 rpm)
Oil Inlet Temperature = 388.7°K ± 1.7° (240°F ± 3°)
Bearing Lubrication = 121 X 10^{-3} kg/sec (16 lb/min)/Bearing

several minutes at 8,896 newtons (2000 lb), the cage speed of the front bearing suddenly decreased from 44.35 to 42.40 percent of shaft speed and was accompanied by a momentary sharp rise in outer ring and oil discharge temperatures. The cage speed returned to only 43.0 percent when the thrust load was reset at 13,344 newtons (3000 lb), but the bearing temperatures returned to their original values. Cage speed and temperatures of the rear bearing remained normal during this time. Since bearing temperatures and rig vibration were not abnormal for either bearing, an attempt was made to determine bearing cage speeds at 3.0 million DN (24,000 rpm). However, rig vibration suddenly increased when 2.9 million DN (23,200 rpm) was reached and testing was discontinued immediately. Data recorded during shutdown revealed that the cage speeds of the front bearing were significantly lower than the cage speeds obtained during startup, as shown in Tables XXXIII and XXXIV, and became progressively lower as shaft speed was reduced. Outer ring and oil discharge temperatures of the front bearing during shutdown were almost identical to the corresponding startup temperatures. Cage speeds and temperatures of the rear bearing were almost identical during shutdown to those obtained on startup.

Inspection revealed that one drilled-ball in the front bearing had fractured into two principal pieces which had wedged together in the cage ball pocket between the two rings. A small splinter-like segment had been ejected from the bearing. The cage was intact and all of the ball restraining pins were firmly in place. The rear bearing, S/N 2552 A-2, was found to be in good condition. Detailed inspection results are presented in the Post-Test Inspection of Drilled-Ball Bearings section.

COMPARISON OF DRILLED-BALL AND SOLID-BALL BEARING TESTS

Analysis of the Task III skid-mapping test results has indicated that the drilled-ball bearing performance was similar to the solid-ball bearing performance up to 2.0 million DN during thrust-load reduction cycles. Both bearing configurations were insensitive to skidding up to 2.0 million DN at the two oil-supply temperatures.

Both bearing configurations experienced reductions in cage speed for the first time at 2.4 million DN, but they did not behave in exactly the same way. Cage speeds for the solid-ball bearings decreased more at 388.7°K (240°F) than at 366.5°K (200°F), but the minimum values at both oil supply temperatures were not low enough to positively indicate ball skidding. Cage speeds for the drilled-ball bearings decreased more at 366.5°K (200°F) than at 388.7°K (240°F), but only the cage speed of the front drilled-ball bearing was low enough (approximately 44.0 percent of shaft speed at both supply temperatures) to suggest ball skidding. It appears that skidding did not occur in the solid-ball bearings at 2.4 million DN. It is believed that the drilled-ball cage speed values are related to incipient skidding which is erratic at 2.4 million DN. Corresponding drilled-ball bearing temperature data obtained during both tests do not substantiate ball skidding at either oil supply temperature.

Cage behavior of the front drilled-ball bearing at 2.8 million DN and 366.5°K (200°F) oil supply temperature was similar to both solid-ball bearings which appeared to have started to skid at 2.8 million DN. Although these cage speed reductions are considered significant, the reductions were not as large as anticipated. Only the cage speed data for the front drilled-ball

bearing are considered reliable at 2.8 million DN and 366.5°K (200°F) because the cage of the rear bearing appeared to be driven by intermittent contact with an adjacent spacer ring. Insufficient data were obtained during the tests at 2.8 million DN and 388.7°K (240°F) because testing was terminated when the front bearing failed.

A comparison of the solid-ball and the drilled-ball bearing temperature data obtained in Task III shows that the drilled-ball bearings ran cooler than the solid-ball bearings at all combinations of thrust load and DN levels. The drilled-ball differential and oil outlet temperatures were generally 2.9°K (5°F) to 11.4°K (20°F) and 5.7°K (10°F) to 14.3°K (25°F) lower than the temperatures of the corresponding solid-ball bearing.

A tabulation of the thermal equilibrium data for the drilled-ball bearing skid-mapping tests is included in columns 14 and 15 of Tables XXI through XXXIV. It is readily apparent that the difference between outer-race and oil-in temperatures (ΔT) changed 1.1°K (2°F) or less during a five minute period of stable operation at the maximum thrust load setting for each DN speed condition. Thermal equilibrium was checked at other combinations of thrust load and DN values during the skid-mapping tests and those results are included in the tables.

Drilled-ball bearings S/N 2600 A-1 and S/N 2600 A-2 accumulated 11.12 hours of running time during the skid-mapping tests at 366.5°K (200°F) oil supply temperature; drilled-ball bearings S/N 2600 A-1 and S/N 2552 A-2 accumulated 9.52 hours running time during the tests at 388.7°K (240°F). The running time for each bearing at each set of operating conditions is presented in Table XXXV.

TABLE XXXV

TASK III DRILLED-BALL BEARING RUNNING TIME
P/N SKN52576 S/N 2600 A-1, S/N 2600 A-2, AND S/N 2552 A-2

Oil Inlet Temperature °K (°F)	1.0×10^6 DN (8000 rpm) hr	1.5×10^6 DN (12000 rpm) hr	2.0×10^6 DN (16000 rpm) hr	2.4×10^6 DN (19,200 rpm) hr	2.8×10^6 DN (22,400 rpm) hr	3.0×10^6 DN (24,000 rpm) hr	Startup/ Shutdown hr	Total*** Bearing Time - hr.
366.5 (200)*	1.75	1.53	1.30	1.40	1.92	--	3.17	11.12
388.7 (240)**	2.11	1.96	1.43	1.26	0.50	--	2.26	9.52
								20.64

*S/N 2600 A-1 and S/N 2600 A-2
**S/N 2600 A-1 and S/N 2552 A-2
***The bearing running time listed is the same for each test bearing.

DRILLED-BALL BEARING FAILURES AND CAGE PIN WEAR DISCUSSION

On the basis of the test data and subsequent post-test bearing inspection, it appears that at least one of the drilled-balls in bearing S/N 2600 A-2 fractured when the shaft speed reached 2.8 million DN during restart of the test rig. Ball fragments apparently were retained within the bearing, eventually causing raceway damage and fracturing additional balls. Because of the extensive rubbing damage, it was not possible to determine which ball fractured initially or the initial failure mode of the fractured balls.

A single drilled-ball in bearing S/N 2600 A-1 fractured and collapsed within its cage ball pocket during the skid test at 2.8 million DN. Electron fractrographic analysis revealed that the initial ball-fracture was a fatigue crack which emanated from a point near the ID wall and propagated toward the ball surface. Rubbing damage prevented determination of the exact origin of the fatigue crack at the bore wall.

Post-test inspection measurements revealed that three intact drilled balls from bearing S/N 2600 A-1 had experienced significant out-of-roundness changes, indicating possible ball deformation. Both failed bearings had operated for the first time at 22,241 newtons (5000 lb) in Task III. Previous tests of these bearings under Contract NAS3-13491 were limited to 13,344 newtons (3000 lb). Post-test out-of-roundness measurement in that program did not show any significant changes. These observations suggest that the drilled balls of this configuration may be distinctly load limited although they have demonstrated considerable potential for high speed operation up to 3.0 million DN.

Post-test inspection of the cage from bearing S/N 2600 A-1 also revealed that a number of drilled balls had heavily contacted the circumferential surfaces of their restraining pins. It is believed that these contact marks had been made during the maximum 22,241 newtons (5000 lb) thrust load and low shaft-speed test conditions. The drilled-ball would be tilted to its greatest contact angle under those conditions. The cage from bearing S/N 2552 A-2, which was exposed only to 13,344 newtons (3000 lb) maximum thrust load in Task III testing, did not exhibit heavy ball-contact marks on its restraining pins. It appears that a bearing thrust load of 13,344 newtons (3000 lb) will not cause drilled-ball tilting beyond the 30 degree angular restraint which is provided by the pin design and ball chamfer. However, it does appear that a bearing thrust load of 22,241 newtons (5000 lb) makes the drilled-ball exceed the maximum allowable 30 degree contact angle and rub hard on the cage pins. Subsequent test results of the Task IV cyclic endurance tests, which were limited to 13,344 newtons (3000 lb) thrust load, also produced a drilled-ball cage free of heavy ball-contact marks on its restraining pins.

POST-TEST INSPECTION OF DRILLED-BALL BEARINGS

A post-test inspection was conducted on each drilled-ball bearing after completion of testing at 366.5°K (200°F) oil supply temperature and again after testing at 388.7°K (240°F). Generally the components of the drilled-ball bearing that had survived the test were in good condition. The first failed bearing, S/N 2600A-2, was extensively damaged including eleven broken balls. The cage was intact and all of the ball restraining pins were firmly in place. The second failed bearing, S/N 2600A-1, contained one fractured ball and a skid pattern on the outer ring raceway. Again, the cage was intact and all pins were attached.

Post-Test Inspection After 366.5°K Test

Front Bearing S/N 2600A-1

The post-test condition of the front bearing, S/N 2600A-1, before disassembly is shown in Figure 22. There were no cracked balls, and the cage was intact. All pins were tightly secured to the cage rails, but they contained ball contact marks on their circumferential surfaces, as shown in Figures 23 and 24. The depth of these marks ranged from approximately two to ten mils.

Previous inspection of this cage following the temporary suspension of testing after 2.8 million DN had revealed that the balls had contacted the pins rather hard and had torn the silver plating, as shown in Figure 25. Ball pocket contact was greater in the cage rotational direction, but pocket wear was not extensive. The silver plating in the cage bore along the rail locations was in excellent condition and contained fewer inner-ring contact marks than the two solid-ball bearing cages. The outer ring and both inner rings were in good condition. Ball tracks were visible on the outer race and on the load-carrying inner race contact surfaces. There was no evidence of ball skidding on the raceway surfaces.

Rear Bearing S/N 2600A-2

The post-test condition of the failed rear bearing, S/N 2600A-2, before disassembly is shown in Figures 26 and 27. Eleven of twenty-one balls were broken and had collapsed in their respective cage pocket. Only one ball-fragment was found wedged between a cage web and both inner ring surfaces. The cage was intact but was jammed against the load-carrying inner ring.

Additional details of the cage are shown in Figures 28, 29, and 30. The ball restraining pins were firmly in place, although all were extensively damaged. The cage bore was heavily scored inside the cage rail on the side that was jammed against the shoulder of the load-carrying inner ring. Contact was relatively light along the rail surface on the opposite side of cage bore. Approximately one-third of the cage circumferential rail surface had contacted heavily both shoulder land-surfaces of the outer ring. Several web OD surfaces were heavily scored by ball fragments.

As shown in Figure 31, the outer ring raceway was badly scored by ball fragments, but there were no surface spalls as best as could be determined. Both shoulder land surfaces of the outer ring exhibited rubbing contact marks from the cage rails. As shown in Figure 32, the shoulder of the load-carrying inner ring was heavily worn and its raceway damaged by ball fragments. The nonload carrying inner ring, also shown in Figure 32, had not been damaged as badly by ball fragments, and its shoulder land surface was in good condition. It also appeared that the raceways of both inner ring configurations were free of surface spalls.

The post-test condition of the twenty-one drilled balls are shown in Figures 33 and 34. Eleven balls were fractured, and a number of the balls had assumed a semicone shape. These particular balls were found to be oriented within the bearing with the smaller-diameter end of the balls in contact with the raceway of the load-carrying inner ring. The various segments of all the broken balls contained evidence of rubbing or skidding. Detailed examination of the various ball fragments suggests that balls No. 9 through No. 12 might have failed through fatigue cracking. However, because of the extensive rubbing damage, it was not possible to positively define surface areas containing fatigue striations.

Post-Test Inspection After 388.7°K Test

Front Bearing S/N 2600A-1

The post-test condition of the front bearing, S/N 2600A-1, before disassembly is shown in Figures 35 and 36. One drilled-ball had fractured into two principal pieces which had wedged themselves in the cage ball pocket, and a small splinter-like segment had been ejected from the bearing. The cage was intact and all of the ball restraining pins were firmly in place.

Additional details of the cage are shown in Figures 37, 38, 39, and 40. Ball pocket contact had been greater in the cage rotational direction, but pocket wear generally was not excessive. The pocket containing the broken ball sustained a small dig-mark on the web side which went through the silver plating to a depth of approximately 10 to 15 mils. The silver plating in the cage bore along the rail locations was in good condition and contained fewer inner ring contact marks than the two solid-ball cages. There was no evidence of cage contact with the outer ring shoulder land surfaces. Ball contact marks on the pin circumferential surfaces had not increased in either quantity or severity. As shown in Table XX, the change in cage unbalance was negligible.

The raceway surface of the outer ring contained a definite skid pattern which had been produced by one of the jammed ball-segments. Surface measurements indicated that material had been removed approximately to a depth of 1.0 mil. Otherwise, the outer ring was in good condition. The raceway surfaces of both inner ring configurations were in good condition and did not contain any evidence of ball skidding. The land-surfaces on the shoulders of both inner ring configurations contained light circumferential rubbing contact marks from the cage rails.

The post-test condition of the fractured drilled ball is shown in Figures 41, 42, and 43. The face of the ball shown in Figure 41 is the segment which was jammed against the outer ring raceway. Figures 42 and 43 show the appearance of the three ball-segments separated from each other. There was no evidence of additional cracks in the bore surfaces of the two principal segments.

Electron fractographic analysis was performed on the broken ball to determine the mode and direction of failure. Two main fracture surfaces were involved in this investigation, surfaces A and B in Figure 44. Replicas, shown in Figures 45 and 46, disclosed that surface A contained vague fatigue striations between rubbed areas indicating that a fatigue crack originated near the ID wall and propagated intermittently along with brittle tearing towards the OD wall. Random fatigue areas were observed just inside the rubbed origin edge to within three-fourths of the total crack length. Beyond that point rubbing damage prevailed again. The exact location of the origin could not be determined because of the presence of rubbing damage.

Replication of failure surface B, shown in Figure 47, displayed a ductile overload fracture suggesting that it occurred as a secondary fracture. This surface was also extensively altered by rubbing damage. No signs of fatigue failure were detected.

Although the extreme origin-edge could not be adequately inspected due to rubbing damage, it appeared that the initial fracture was a fatigue crack in surface A which emanated from near the ID wall and propagated toward the ball surface. Final ball separation occurred by ductile overload.

The post-test condition of the intact drilled-balls can be seen in Figure 48. Five representative balls out of the twenty intact balls are shown. The balls showed some orbital lines and wear tracks near the ball equator. The wear tracks were the result of contact with the outer race after its raceway was disturbed by the fractured ball. The twenty balls had retained their original color and did not contain any cracks in their bore surface. Material appeared to have transferred from the cage pins onto the chamfer surfaces of a number of drilled balls. Two balls were found to contain an area of pits or micro-spalls in their bore wall as shown in Figure 49.

Pretest and post-test measurements of ball bore diameters and ball out-of-roundness revealed no change in bore diameter but that three balls had changed out-of-roundness significantly. These balls were 60, 70, and 220 millionths out-of-round while the remaining balls had retained approximately their pretest values, ranging between 20 to 40 millionths out-of-round.

Rear Bearing S/N 2552A-2

Inspection revealed that the inner and outer rings, cage, and drilled balls of the rear bearing, S/N 2552A-2, were in good condition. Ball tracks were evident on the outer race and on the load-carrying inner-race contact surfaces. The nonload carrying inner race did not contain any ball tracks. There was no evidence of ball skidding on any raceway surface. The land-surfaces on the shoulders of both inner-ring configurations contained light circumferential rubbing contact marks from the cage rails.

The cage was intact, and all pins were tightly secured to the cage rails. A few pins contained very light ball contact marks on their original circumferential surfaces. (The silver plating had been removed from the cage pins prior to Task III testing because the plating bond was poor.) The silver plating in the cage bore along the rail locations was in good condition and contained fewer inner ring contact marks than the solid-ball cages. There was no evidence of contact between the cage OD rail surfaces and the outer ring shoulder land-surfaces. Ball pocket contact had been greater in the cage rotational direction, but pocket wear was not excessive. As shown in Table XX, the cage unbalance increased very slightly from 1.5 to 2.0 gm-cm.

All of the drilled balls were intact, did not contain any bore cracks, and retained a straw color. Post-test ball measurements revealed that there were no significant variations in bore diameters and that ball out-of-roundness ranged between 20 and 30 millionths.

Figure 22   Post-Test Appearance of Drilled-Ball Bearing S/N 2600A-1 Before Disassembly With Load-Carrying Inner Ring Removed

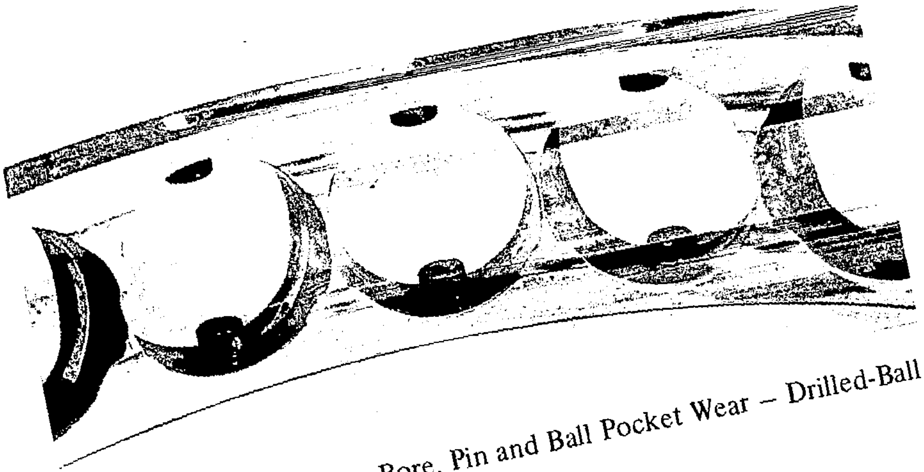


Figure 23 Appearance of Cage Bore, Pin and Ball Pocket Wear – Drilled-Ball Bearing S/N 2600A-1

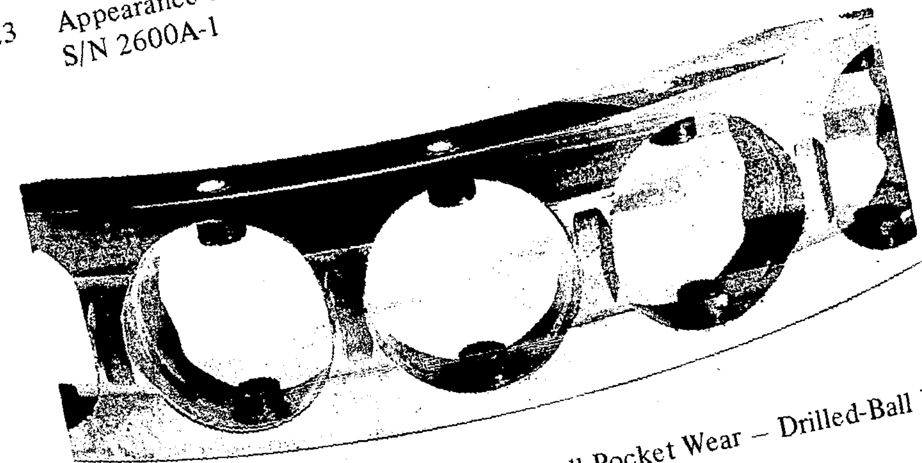


Figure 24 Appearance of Cage Pin and Ball Pocket Wear – Drilled-Ball Bearing S/N 2600A-1

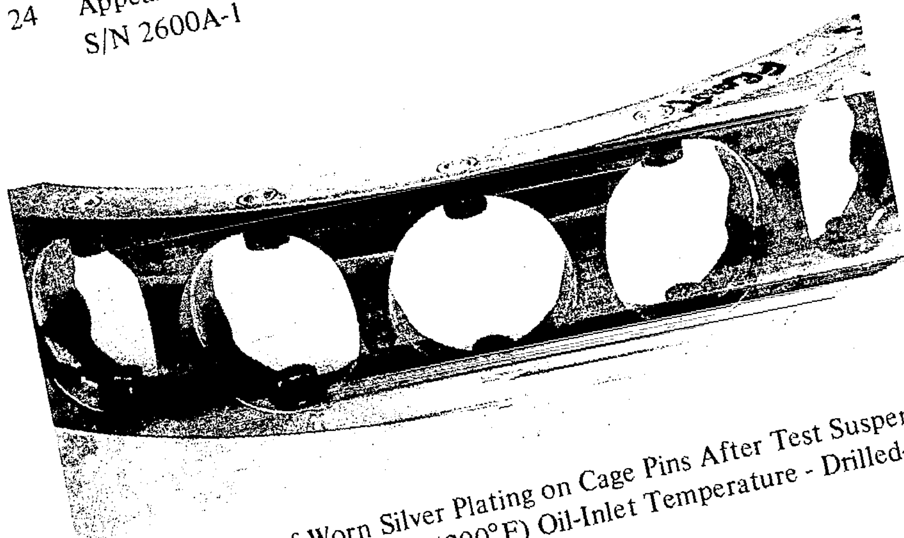


Figure 25 Appearance of Worn Silver Plating on Cage Pins After Test Suspension at 2.8 Million DN and 366.5°K (200°F) Oil-Inlet Temperature - Drilled-Ball Bearing S/N 2600A-1

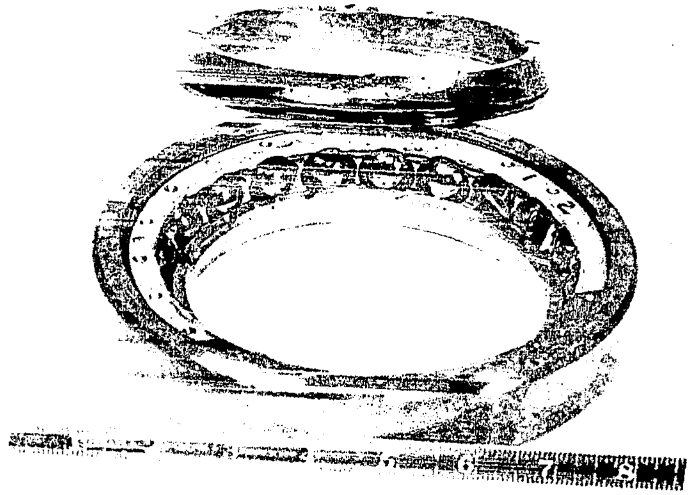


Figure 26 Post-Test Appearance of Drilled-Ball Bearing S/N 2600A-2 Before Disassembly With Thrust-Loaded Inner Ring Removed

Figure 27 Post-Test Appearance of Drilled-Ball Bearing S/N 2600A-2 Before Disassembly With Thrust-Loaded Inner Ring Removed

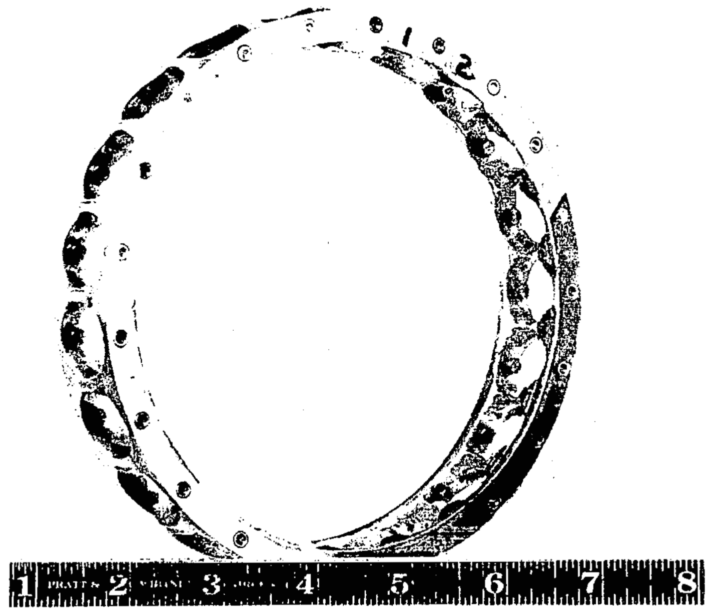


Figure 28 Overall View of Damaged Cage – Drilled-Ball Bearing S/N 2600A-2

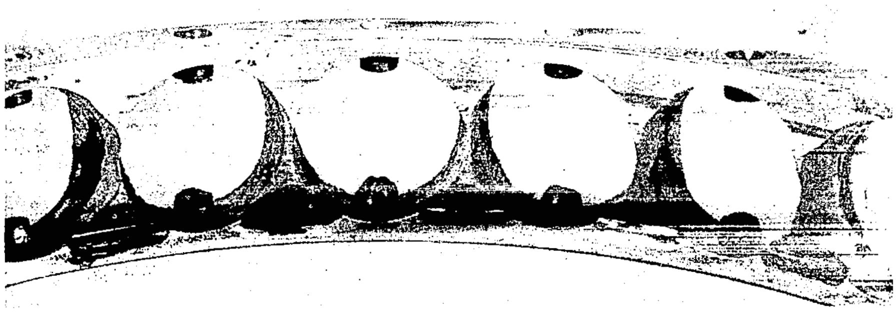


Figure 29 Appearance of Cage Bore, Pin and Ball Pocket Damage – Drilled-Ball Bearing S/N 2600A-2

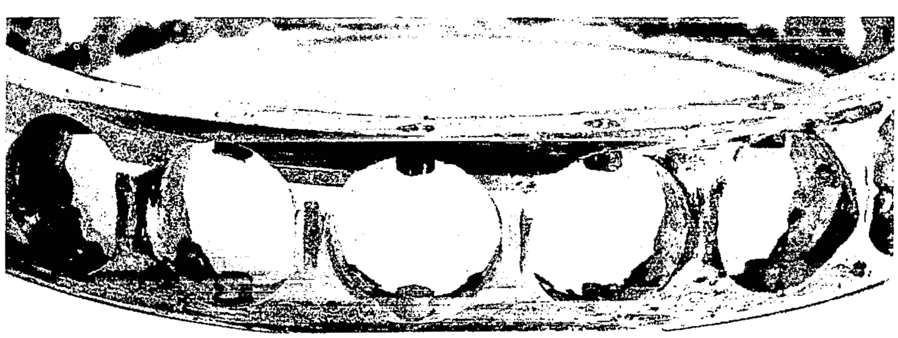


Figure 30 Appearance of Cage OD Surface, Pin and Ball Pocket Damage – Drilled-Ball Bearing S/N 2600A-2

Figure 31 Appearance of Damaged Outer Ring – Drilled-Ball Bearing S/N 2600A-2

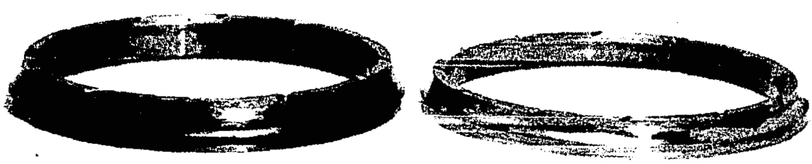


Figure 32 Appearance of Damaged Thrust-Loaded Inner Ring (Left) and Unloaded Inner Ring (Right) – Drilled-Ball Bearing S/N 2600A-2

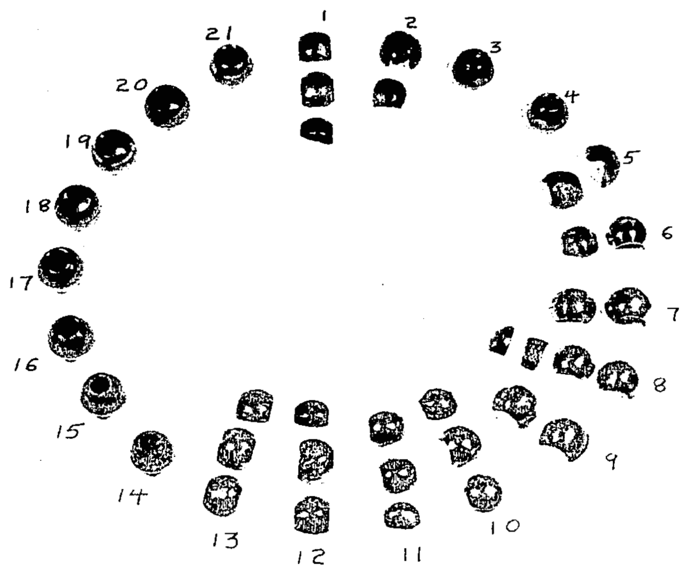


Figure 33 Appearance of Twenty-One Damaged Drilled Balls – Drilled-Ball Bearing S/N 2600A-2

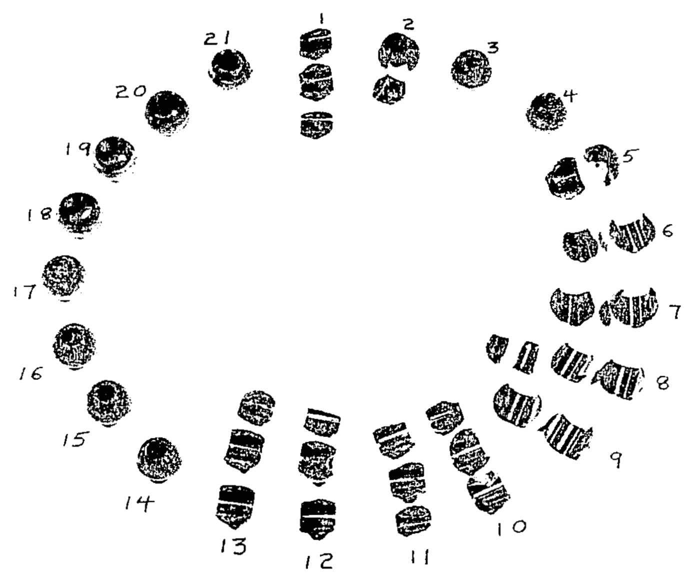


Figure 34 Appearance of Twenty-One Damaged Drilled Balls – Drilled-Ball Bearing S/N 2600A-2

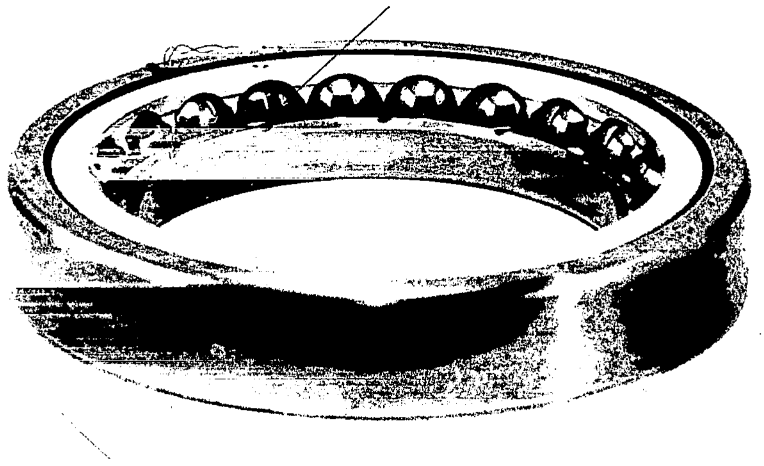


Figure 35 Post-Test Appearance of Drilled-Ball Bearing S/N 2600A-1 Before Disassembly Containing One Fractured Drilled Ball

Figure 36 Close-up View of Fractured Drilled Ball In Cage Ball Pocket Before Bearing Disassembly – Drilled-Ball Bearing S/N 2600A-1

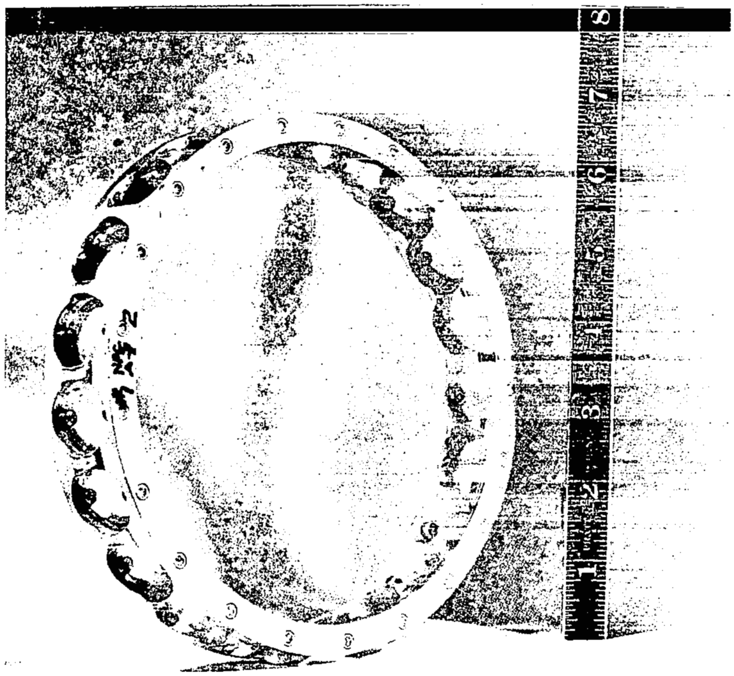


Figure 37 Overall View of Cage – Drilled-Ball Bearing S/N 2600A-1

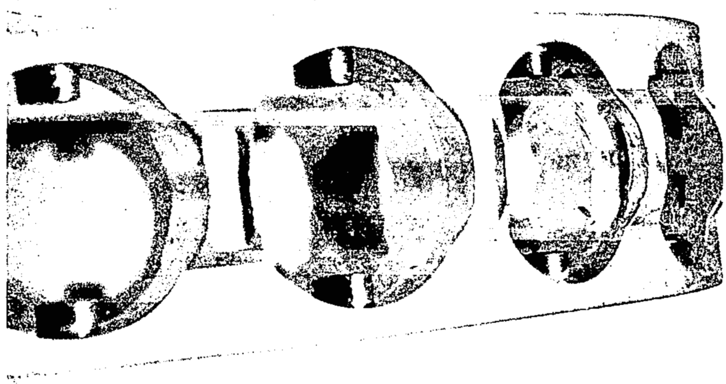


Figure 38 Appearance of Dig-Mark in Ball Pocket Which Contained Fractured B:
Drilled-Ball Bearing S/N 2600A-1

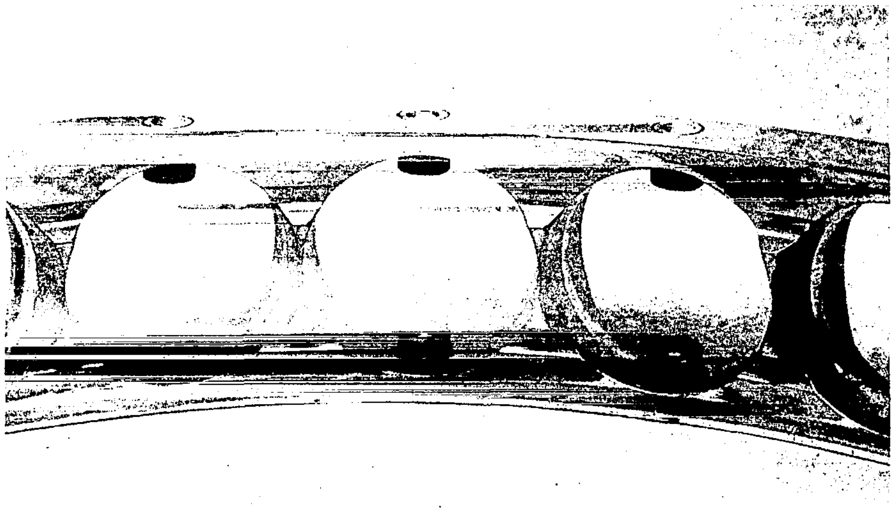


Figure 39 Appearance of Cage Bore, Pin and Ball Pocket Wear – Drilled-Ball Bearing S/N 2600A-1

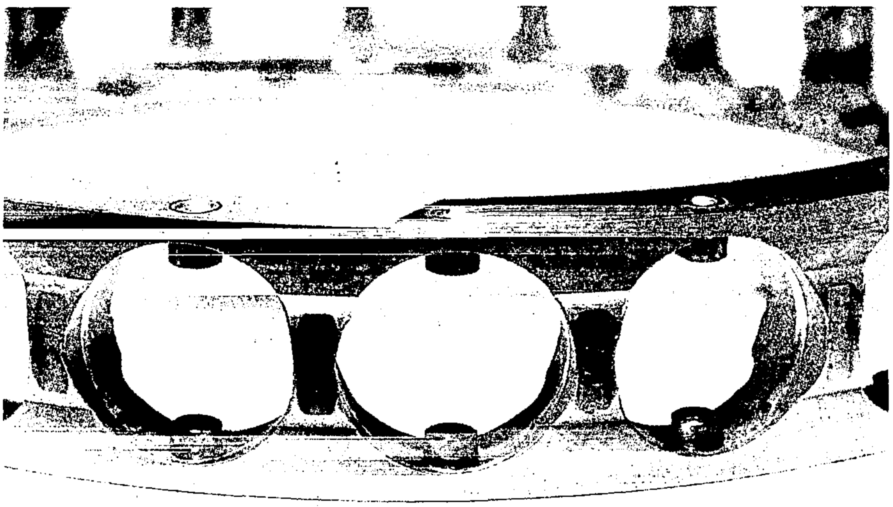


Figure 40 Appearance of Cage OD Surface, Pin and Ball Pocket Wear – Drilled-Ball Bearing S/N 2600A-1

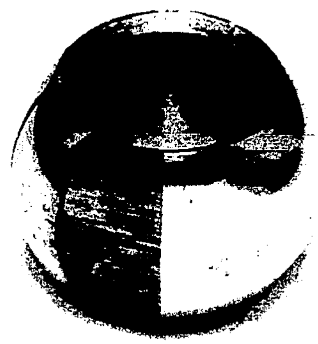


Figure 41 Close-up View of Fractured Drilled-Ball – Drilled-Ball Bearing S/N 2600A-1

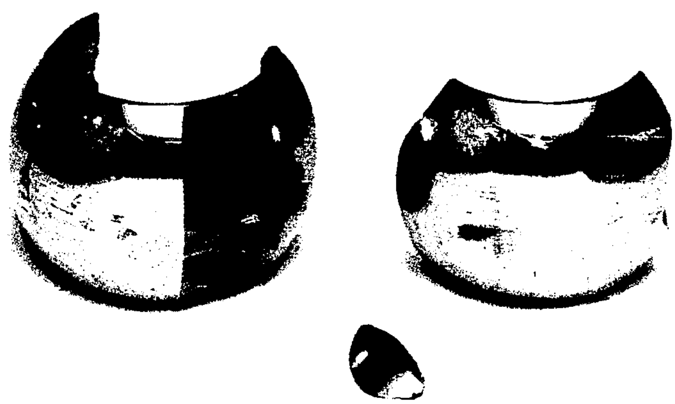


Figure 42 Close-up View of Fractured Drilled-Ball Segments – Drilled-Ball Bearing S/N 2600A-1

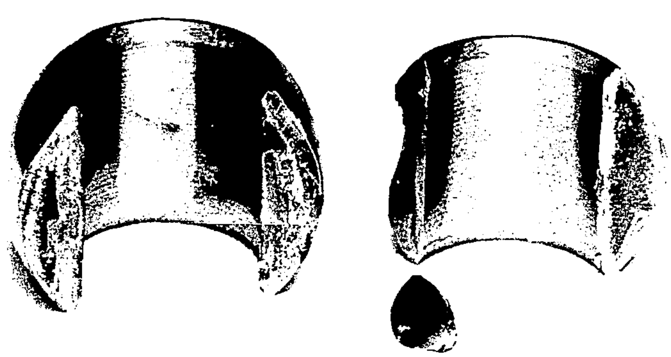


Figure 43 Close-up View of Fractured Drilled-Ball Segments – Drilled-Ball Bearing S/N 2600A-1

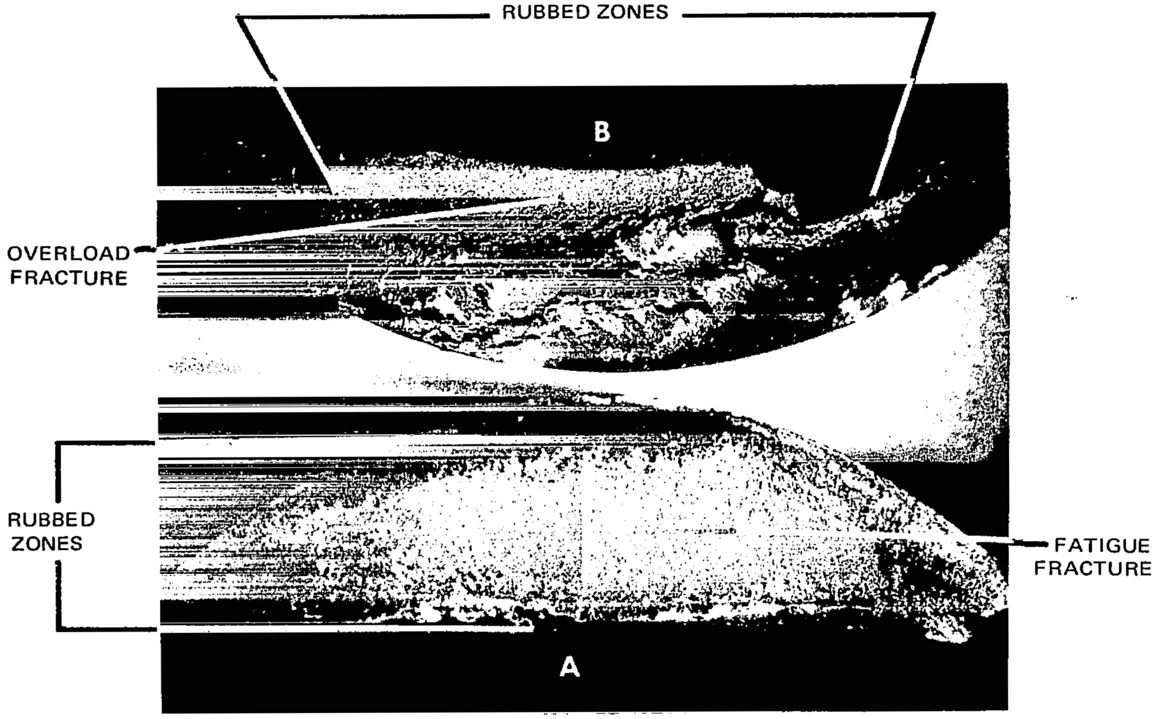


Figure 44 Optical Photomicrograph of Two Main Fracture Surfaces Showing Various Fracture Areas and Direction of Fatigue Crack Propagation (Arrow Indicates Initial Crack Direction) 6X

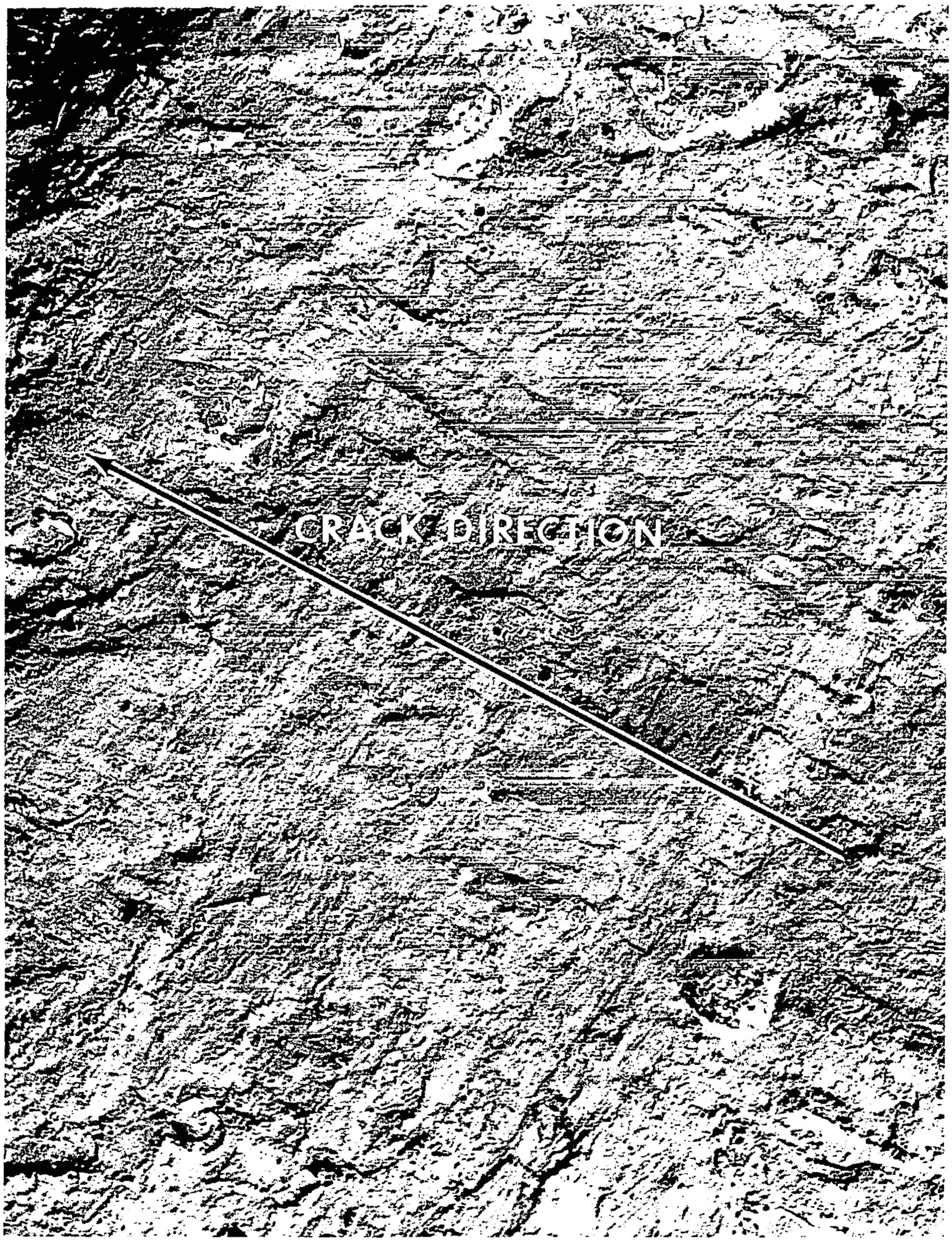


Figure 45 Example of Vague Fatigue Striations Found Between Rubbed Areas of Fracture Surface "A" (Arrow Indicates Crack Direction) X12,000

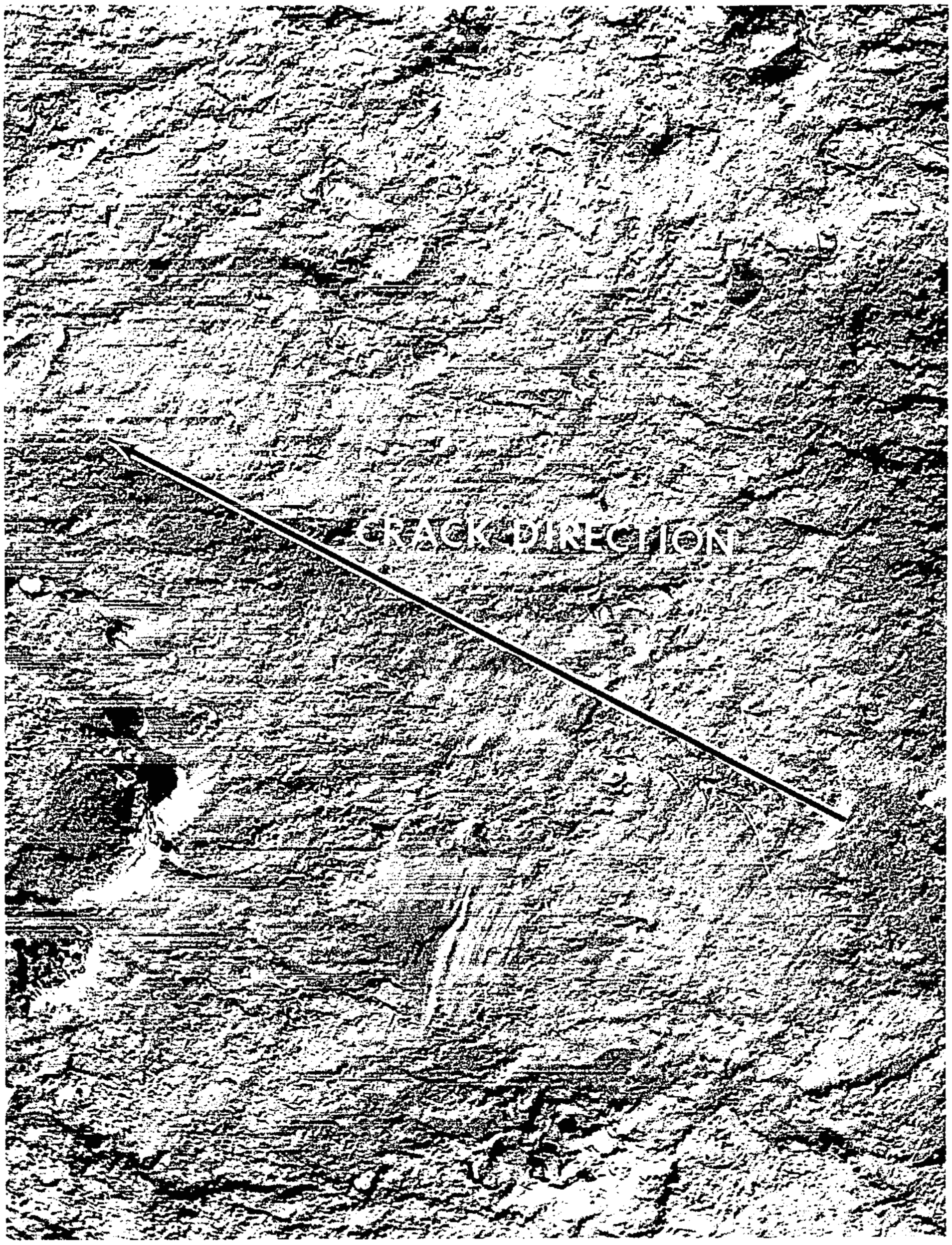


Figure 46 Example of Vague Fatigue Striations Found Between Rubbed Areas of Fracture Surface "A" (Arrow Indicates Crack Direction) X12,000

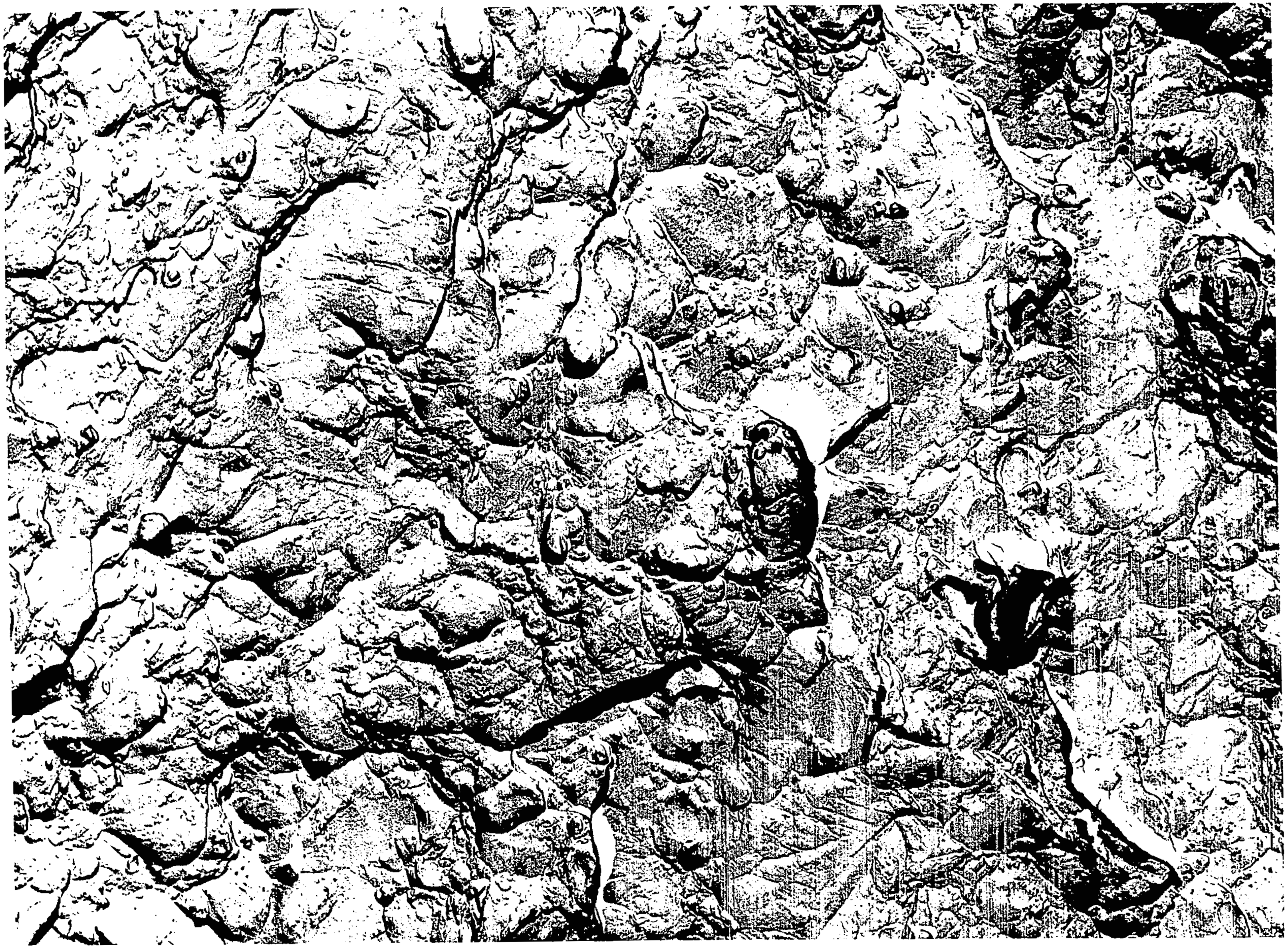


Figure 47 Example of Ductile Overload Found on Fracture Surface "B" (X12,000)

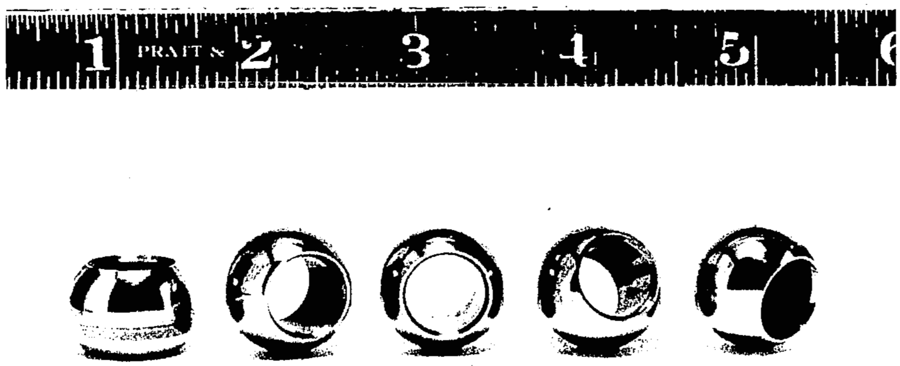


Figure 48 Appearance of Typical Intact Drilled Balls – Drilled-Ball Bearing S/N 2600A-1

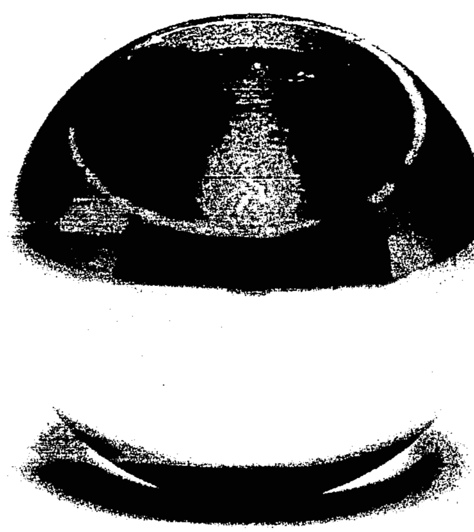


Figure 49 Close-up View of Drilled-Ball Containing an Area of Pits or Micro-Spalls in Bore Wall – Drilled-Ball Bearing S/N 2600A-1

TASK IV CYCLIC ENDURANCE TESTS

Testing in Tasks II and III of this contract was directed towards the accumulation of basic performance data regarding drilled-ball bearings. Bearing behavior over a range of oil supply flows and bearing responses to skidding conditions were investigated. Although this information was of primary interest, it also was necessary to demonstrate the ability of drilled-ball bearings to start and stop repeatedly. This was considered particularly important because it appeared likely that the principal interactions between the drilled balls and their restraining elements would occur during startup and shutdown. Therefore, Task IV was undertaken to determine drilled-ball bearing durability in cyclic operation.

TEST PROCEDURE AND CONDITIONS

The typical endurance-cycle presented in Table XXXVI consisted of bearing startup to 2.6 million DN (shaft speed 20,800 rpm), a one-hour endurance run at 2.6 million DN at constant operating conditions, and bearing shutdown to zero rpm.

TABLE XXXVI

TYPICAL TASK IV ENDURANCE CYCLE

STARTUP

1. Set rig shaft speed at 1000 rpm
2. Increase bearing thrust load to 1,112-1,668 newtons (250-375 lb)
3. Increase rig speed to 6000 rpm
4. Increase thrust load to 4,448 newtons (1000 lb)
5. Increase rig speed to 8000 rpm
6. Increase thrust load to 13,344 newtons (3000 lb)
7. Increase rig speed to 20,800 rpm (2.6 million DN)

ONE-HOUR ENDURANCE RUN AT 2.6 MILLION DN

Temperature:	Oil in 383.15° - 388.71°K (230°-240°F)
Oil Flow Rate:	121 x 10^{-3} Kg/sec (16 lb/min)/bearing
Thrust Load:	13,344 newtons (3000 lb)/bearing

TABLE XXXVI (Cont'd)

SHUTDOWN

1. Decrease rig shaft speed to 8000 rpm
2. Decrease bearing thrust load to 4,448 newtons (1000 lb)
3. Decrease rig speed to 6000 rpm
4. Decrease thrust load to 2,224 newtons (500 lb)
5. Decrease rig speed to 4000 rpm
6. Decrease thrust load to 1,112-1,668 newtons (250-375 lb)
7. Decrease rig speed to 1000 rpm
8. Decrease rig speed and thrust load simultaneously to zero

It was originally planned to run two drilled-ball bearings during Task IV. However, only one drilled-ball bearing was in condition for further testing after the bearing failures sustained during Tasks II and III. As a result, the test program was changed to run one solid-ball and one drilled-ball bearing until forty consecutive endurance cycles were completed. Endurance testing was to be terminated if the drilled-ball bearing failed before completion of the forty cycles.

CYCLIC ENDURANCE TEST RESULTS

Representative temperature and cage speed data for the solid-ball bearing S/N 2560 A-1 and the drilled-ball bearing S/N 2552 A-2 are presented in Figure 50 for the one hour running period at 2.6 million DN in each cycle. Endurance testing was discontinued after the 25th cycle when it was observed that the cage speed of the drilled-ball bearing changed significantly during shutdown. Inspection of the bearing revealed that one drilled-ball had fractured into two principal pieces which had wedged together in the cage ball pocket between the two rings. A small splinter-like segment had been ejected from the bearing. The cage was intact and all of the ball restraining pins were firmly in place. The solid-ball bearing was found to be in good condition. Detailed inspection results are presented in the Post-Test Bearing Inspection section.

The oil-inlet temperature was maintained at 383.15° to 388.71°K (230°-240°F) during the 25 endurance cycles. The two bearings demonstrated almost identical performance from the first through the 24th cycle, as shown in Figure 50. The average oil discharge temperatures from both bearings generally ranged between 433.1°K (320°F) and 438.7°K (330°F). The average outer race oil inlet temperature differentials generally ranged between 52.8°K (95°F) and 58.3°K (105°F). The drilled-ball bearing ran slightly warmer than the solid-ball bearing through the first 24 cycles by approximately 2.75°K (5°F). The cage speeds of both bearings ranged between 44.5 and 45.5 percent of shaft speed.

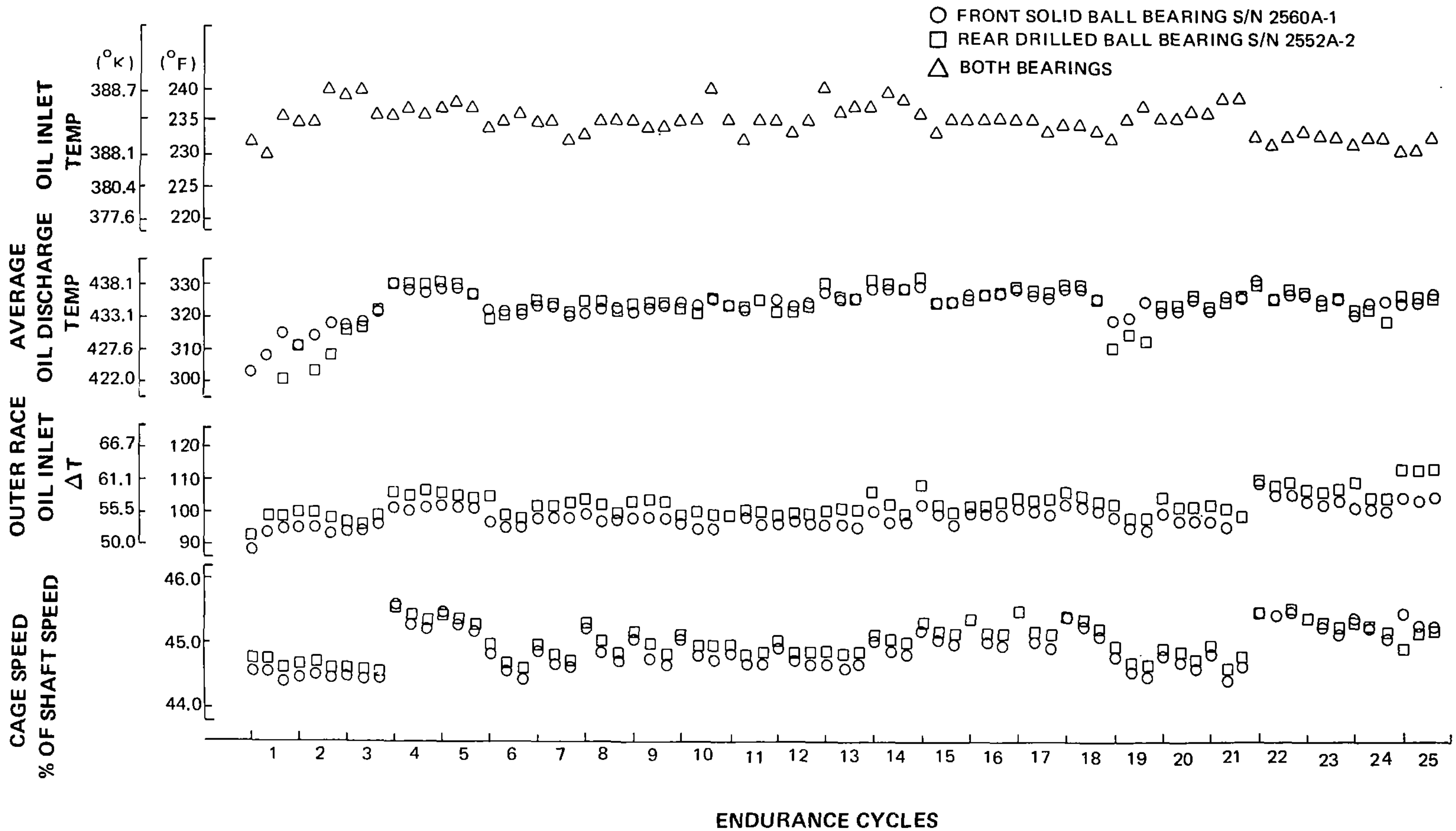


Figure 50 Task IV Cyclic Endurance Test
Endurance Speed = 2.6 Million DN (20,800 rpm)
Max. Thrust Load = 13344 N (3000 lb)/Bearing
Bearing Lubrication = 121 X 10^{-3} kg/sec (16 lb/min)/Bearing

During shutdown in the 25th cycle, it was observed that the cage speed of the drilled-ball bearing at 8000 rpm (1.0 million DN) had decreased to 37.8 percent of shaft speed compared to 44.5 percent during startup of the 25th cycle. Cage speed values of the solid-ball bearing during startup and shutdown were almost identical, approximately 44.6 percent of shaft speed at 8000 rpm. During the one-hour endurance run at 2.6 million DN in the 25th cycle, the drilled-ball cage speed was initially 45.5 percent and then ranged between 45.1 and 45.3 percent until shutdown was started. Solid-ball bearing cage speed values also were normal during the one-hour endurance run, ranging between 45.2 and 45.5 percent of shaft speed. Temperatures of both bearings appeared to be normal, as in previous cycles, and there was no change in rig vibration to indicate abnormal bearing performance.

On startup of the 26th cycle, the drilled-ball cage speed at 8000 rpm was 39.5 percent instead of the normal 44.0 to 44.5 percent, and at 16,000 rpm the speed was 43.1 percent instead of the normal 44.9 to 45.2 percent. Bearing temperatures were normal, but it was decided to discontinue testing and inspect the drilled-ball bearing for possible damage. Inspection revealed that one drilled-ball had fractured.

Close examination of the Bristol Recorder temperature data revealed that the temperatures of both bearings were normal for the first nine minutes of running in the 25th cycle at 2.6 million DN and were similar to the previous 24 cycles. At this point, the outer ring temperature of the drilled-ball bearing suddenly increased by 7.9°K (14°F) in fifteen seconds, becoming approximately 9.6°K (17°F) warmer than the solid-ball bearing. Within two minutes the drilled-ball outer ring temperature decreased by 4.0°K (7°F) and stabilized at 5.7°K (10°F) warmer than the solid-ball bearing for the remainder of the 25th cycle at 2.6 million DN. The temperatures of the solid-ball bearing remained relatively constant during the 25th cycle at 2.6 million DN.

On the basis of the test data and subsequent post-test bearing inspection, it appeared that one of the drilled balls in bearing S/N 2552 A-2 experienced a fatigue fracture and collapsed within the cage ball pocket at approximately ten minutes after the 2.6 million DN shaft speed was set in the 25th endurance cycle. There was no significant change in cage speed and only a slight change in the drilled-ball bearing outer ring temperature. A larger reduction in cage speed was observed when the shaft speed was reduced to 1.0 million DN (8000 rpm) during the shutdown procedure.

Each test bearing accumulated 36.12 hours running time during the Task IV cyclic endurance tests. The running time consisted of 9.08 hours of startup, 25 hours at 2.6 million DN, and 2.04 hours of shutdown.

Inspection also revealed that the drilled balls had not excessively or roughly contacted the circumferential surfaces of the restraining pins during the startup and shutdown sequences of each endurance cycle. Their appearance was quite different from the post test appearance of the cage pins in bearing S/N 2600 A-1 which survived the skid mapping tests which started at a maximum thrust load of 22,241 newtons (5000 lb). That particular cage exhibited severe ball contact marks on the restraining pins which are believed to have occurred at the maximum thrust load and low shaft speed test conditions. The drilled-ball would be tilted

to its greatest contact angle under those conditions. It appears that a bearing thrust load of 13,344 newtons (3000 lb) will not cause drilled-ball tilting beyond the 30 degree angular restraint provided by the pin design and ball chamfer. However, it does appear that a bearing thrust load of 22,241 newtons (5000 lb) makes the drilled ball exceed the maximum allowable 30 degree contact angle and rub hard on the cage pins. This conclusion was also reached at the end of Task III bearing tests.

POST-TEST BEARING INSPECTION

The post-test condition of the solid-ball and drilled-ball bearings is shown in Figures 51 and 52. Generally, the inner rings, outer rings, and cages of both bearings were in good condition. One drilled-ball from the rear bearing (S/N 2552 A-2) was fractured into two principal pieces which had wedged themselves in the cage ball pocket. A small segment had been ejected from the drilled-ball bearing.

Front Solid-Ball Bearing (S/N 2560 A-1)

Ball tracks were evident on the outer-race and on the load-carrying inner-race contact surfaces. The color of these rings was straw. The nonload carrying inner-race did not show any ball track and retained a very faint straw color. The land-surfaces on the shoulders of both inner-ring configurations showed light circumferential rubbing contact marks from the cage rails.

The appearance of the solid-ball cage is shown in Figures 53 and 54. Ball pocket contact had been greater in the cage rotational direction, but pocket wear was not excessive. The silver plating in the cage bore along the rail locations was polished through contact with the land surfaces of the inner rings. As shown in Table XX, there was a slight change in the cage balance. However, the balance change cannot be related directly to the Task IV cyclic endurance tests because this cage was run previously in Task III and a post test balance-check was not taken at that time. It is of importance to note that the change in cage balance resulting from Task III and IV amounted to only 1.0 gm-cm; Tasks III and IV testing totaled approximately 35 hours of running at 2.6 million DN and higher.

Typical ball surface appearances are shown in Figure 55. The balls did show some orbital markings but were generally in good condition and retained a faint straw color. None of the balls showed any evidence of skidding.

Rear Drilled-Ball Bearing (S/N 2552 A-2)

Figure 56 shows the post-test condition of the drilled-ball bearing before disassembly. Only one drilled-ball, as noted in Figure 56, was fractured, and all the other balls were in good condition. The cage was intact and all pins still tightly secured to the cage rails. The outer race surface contained a skid pattern due to the fractured ball segment which was jammed against the raceway. The outer ring was a light straw color. A ball track was evident on the load-carrying inner-race contact surface. Slight nicks were found adjacent to the ball track at several locations in the raceway, but these nicks were produced in testing under Contract

NAS3-13491. The color of this ring was straw. The nonload carrying inner-race did not contain any ball tracks or evidence of ball skidding and retained a very faint straw color. The land-surfaces on the shoulders of both inner-ring configurations contained light circumferential rubbing contact marks from the cage rails.

Additional details of the cage are shown in Figures 53 and 57. Contact with both inner-rings had been relatively light, considerably less than the inner-ring contact experienced by the solid-ball cage. As shown in Table XX, the change in cage unbalance was negligible. Ball-pocket contact had been greater in the cage rotational direction but had not penetrated the silver plating.

Prior to Task IV testing, a few pins contained very light ball contact marks on their original circumferential surfaces. After termination of Task IV testing, ball contact marks on the cage pins were not heavy and did not appear to have increased in quantity.

Figures 58, 59, and 60 show the post-test condition of the fractured drilled ball. The face of the ball shown in Figure 58 contains a crack which subsequently was identified as a fatigue fracture. A small splinter-like segment was expelled from the ball surface adjacent to the crack. Figure 59 shows the face of the ball segment which was jammed against the outer-ring raceway. Located to the right of the skid mark is another crack which was identified as an overload fracture. Figure 60 is an open view of the fractured ball showing the ends of the three pieces and their relationship to each other.

Electron fractographic analysis was performed on the fractured ball to determine the mode and direction of failure. Two main fracture surfaces were involved in this investigation, surfaces A and B in Figure 61. Replicas obtained from just within the ID fracture edge of surface A exhibited an almost continuous array of fine fatigue striations occasionally interrupted by brittle tearing and cleavage of second phase particles; this is shown in Figure 62. The direction of fatigue propagation was oriented away from the ID wall; however, the exact origin location could not be determined because of the presence of rubbing marks.

Inspection of the middle portions of the fatigue crack indicated that two load levels were in operation during fracture, one occurring at a rate of about 12 cycles per micron and the other at two cycles per micron. This is shown in Figure 63. It was not possible to determine the full extent of the dual loading because of the existing rubbing damage.

Replication of failure surface B displayed a ductile fracture mode consisting of various size void formations with a random distribution of cleaved second phase particles. This is shown in Figure 64. No signs of fatigue failure were detected.

The existence of much rubbing-damage along the ID wall of the fracture did not permit sufficient examination of the original edge to positively conclude the initial mode of failure. Judging from the limited area that remained free of rubbing, it appears that fracture of surface A originated at, or close to, the ID wall and propagated towards the OD wall primarily by fatigue and occasionally by brittle tear. Ultimate ball-failure occurred as a result of ductile overload.

Figure 65 shows the post-test condition of five representative balls out of the twenty intact drilled-balls. The balls showed some orbital lines and wear tracks near the ball equator. The wear tracks are a result of contact with the outer race after its raceway was disturbed by the fractured drilled ball. These balls retained a straw color, and were free of cracks in the bore surface. The ball chamfer surfaces did not exhibit any evidence of material transfer from the cage pins.

Pretest and post-test measurements of ball bore diameters and ball out-of-roundness revealed that there was no change in bore diameter but that ball out-of-roundness had changed slightly. Prior to Task IV testing, all 21 balls were found to have a 20-30 millionths out-of-roundness. Post-test measurements revealed that only six balls had retained the pretest values; six balls were 40 millionths and eight balls were 50 millionths out-of-round.

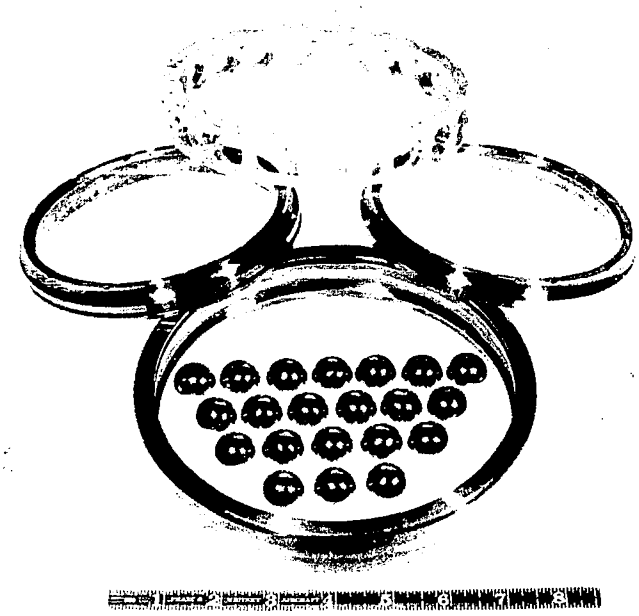


Figure 51 Overall View of Solid-Ball Bearing S/N 2560A-1 After 25 Endurance Cycles

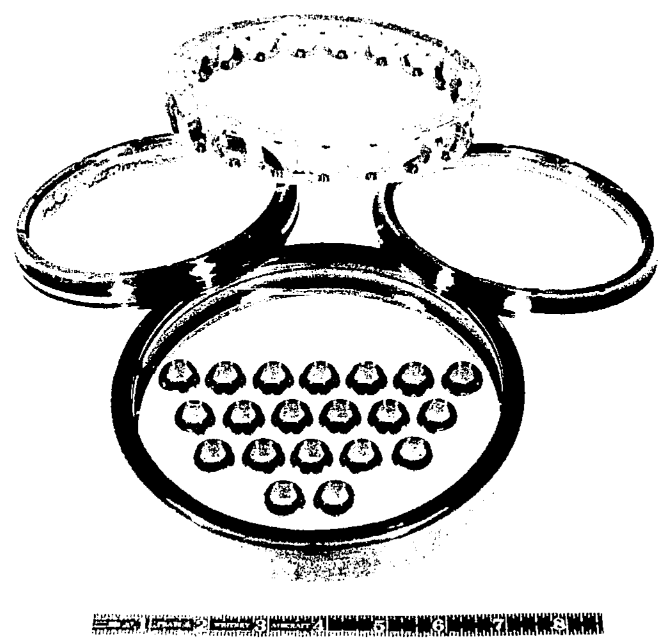


Figure 52 Overall View of Drilled-Ball Bearing S/N 2552A-2 After 25 Endurance Cycles

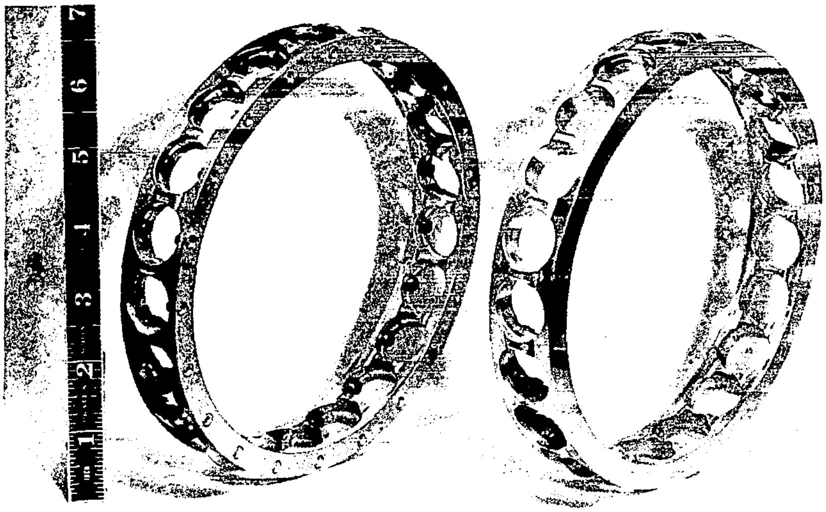


Figure 53 Overall Views of Solid-Ball Cage S/N 2560A-1 and Drilled-Ball Cage S/N 2552A-2

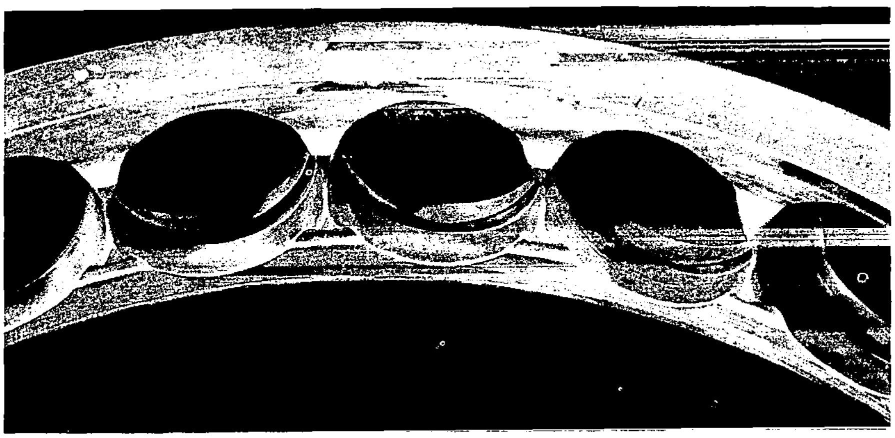


Figure 54 Appearance of Cage Bore and Ball Pocket Wear – Solid-Ball Bearing S/N 2560A-1

Figure 55 Appearance of Typical Solid Balls – Solid-Ball Bearing S/N 2560A-1

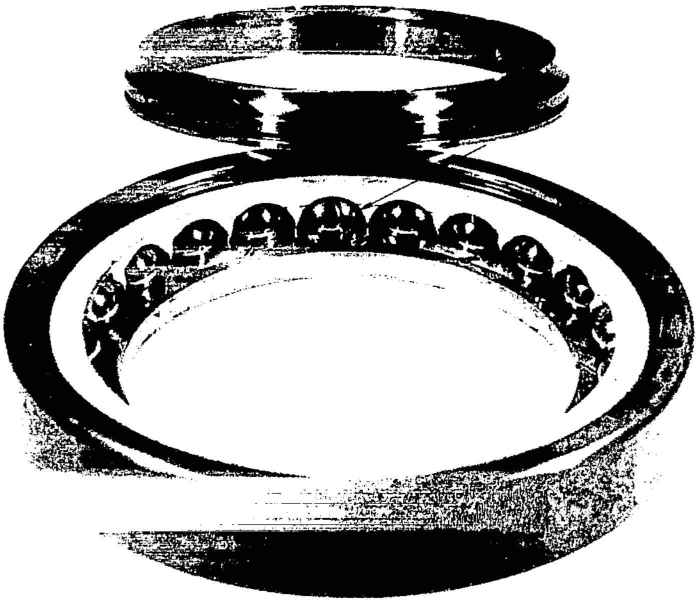


Figure 56 Post-Test Appearance of Drilled-Ball Bearing S/N 2552A-2 Containing One Fractured Drilled-Ball Before Disassembly

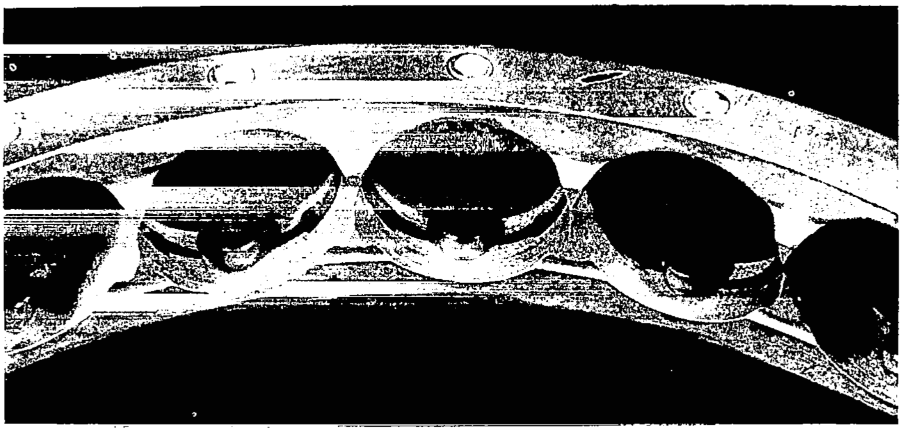


Figure 57 Appearance of Cage Bore, Pin and Ball Pocket Wear – Drilled-Ball Bearing S/N 2552A-2

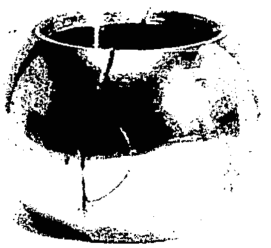


Figure 58 Close-up View of Fractured Drilled-Ball Showing Face Containing Fatigue Crack – Drilled-Ball Bearing S/N 2552A-2

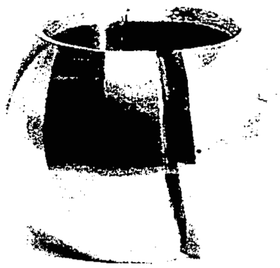


Figure 59 Close-up View of Fractured Drilled-Ball Showing Face Containing Overload Crack and Skid Damage – Drilled-Ball Bearing S/N 2552A-2

Figure 60 Close-up View of the Fractured Drilled-Ball Segments – Drilled-Ball Bearing S/N 2552A-2

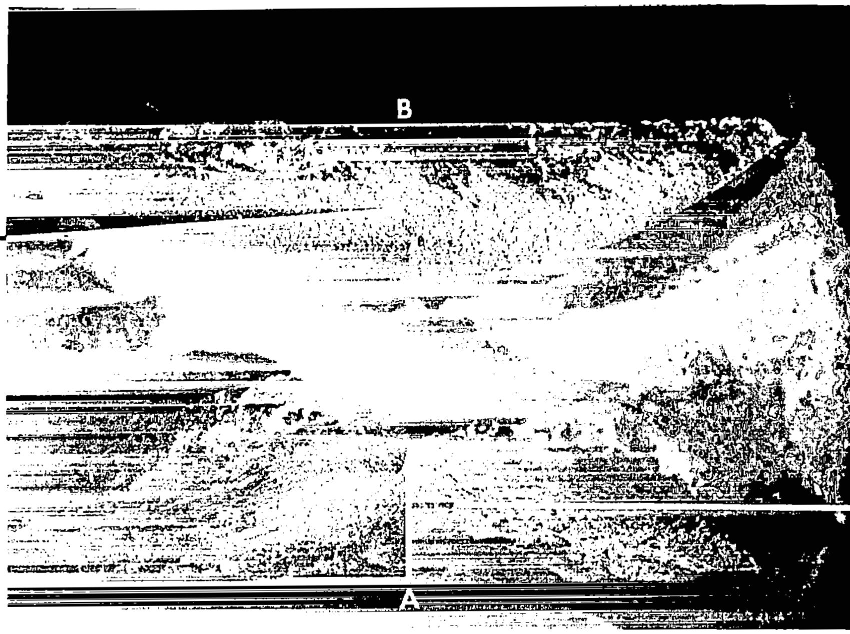


Figure 61 Optical Photomicrograph of the Two Main Fracture Surfaces A & B Showing the Various Fracture Areas and the Direction of Fatigue Crack Propagation (Arrow Indicates Initial Crack Direction) X6

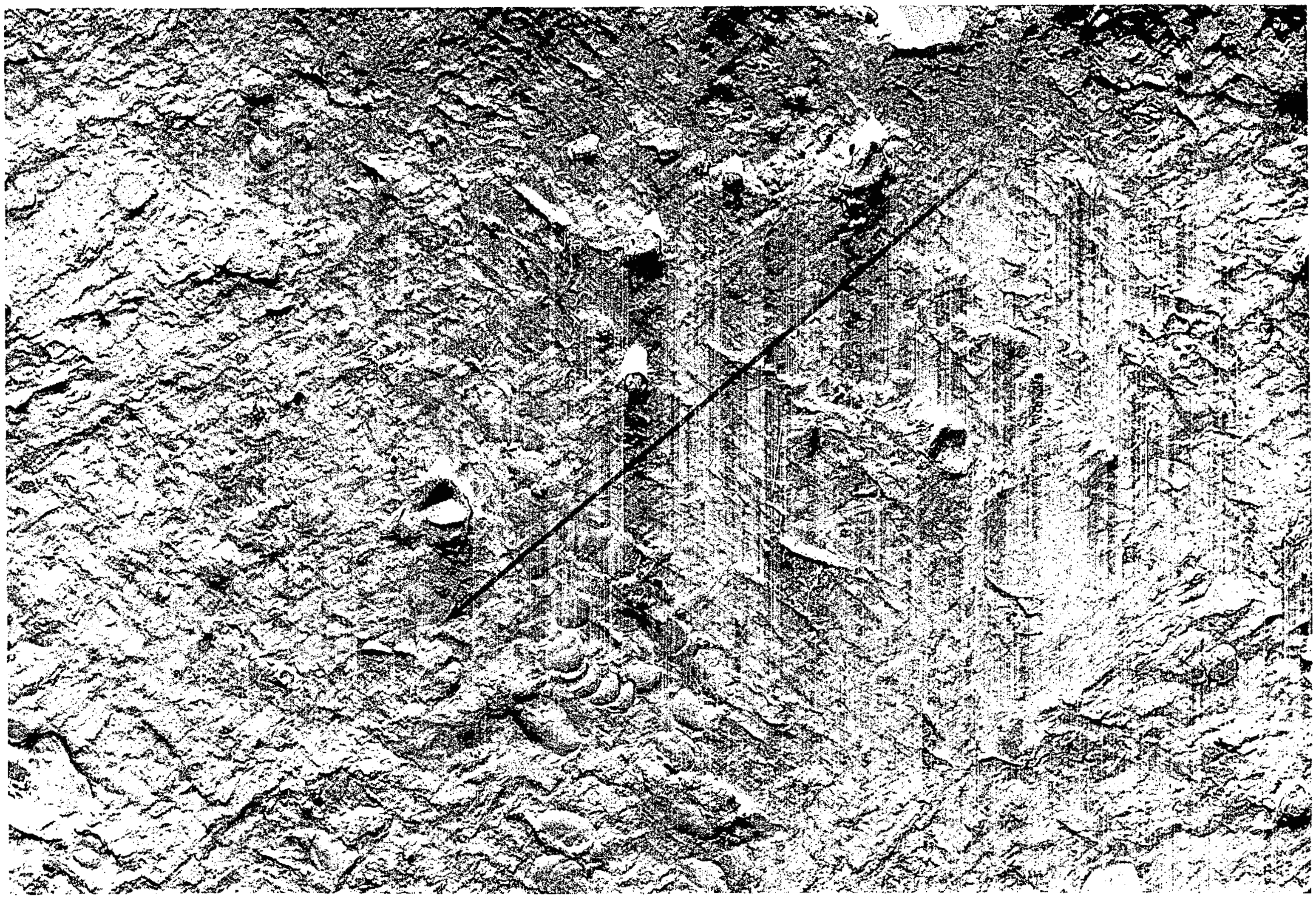


Figure 62 Example of Fatigue Striations Located Just Within Rubbed Area of ID Wall of Fracture Surface A (Arrow Indicates Crack Direction) (X12,000)

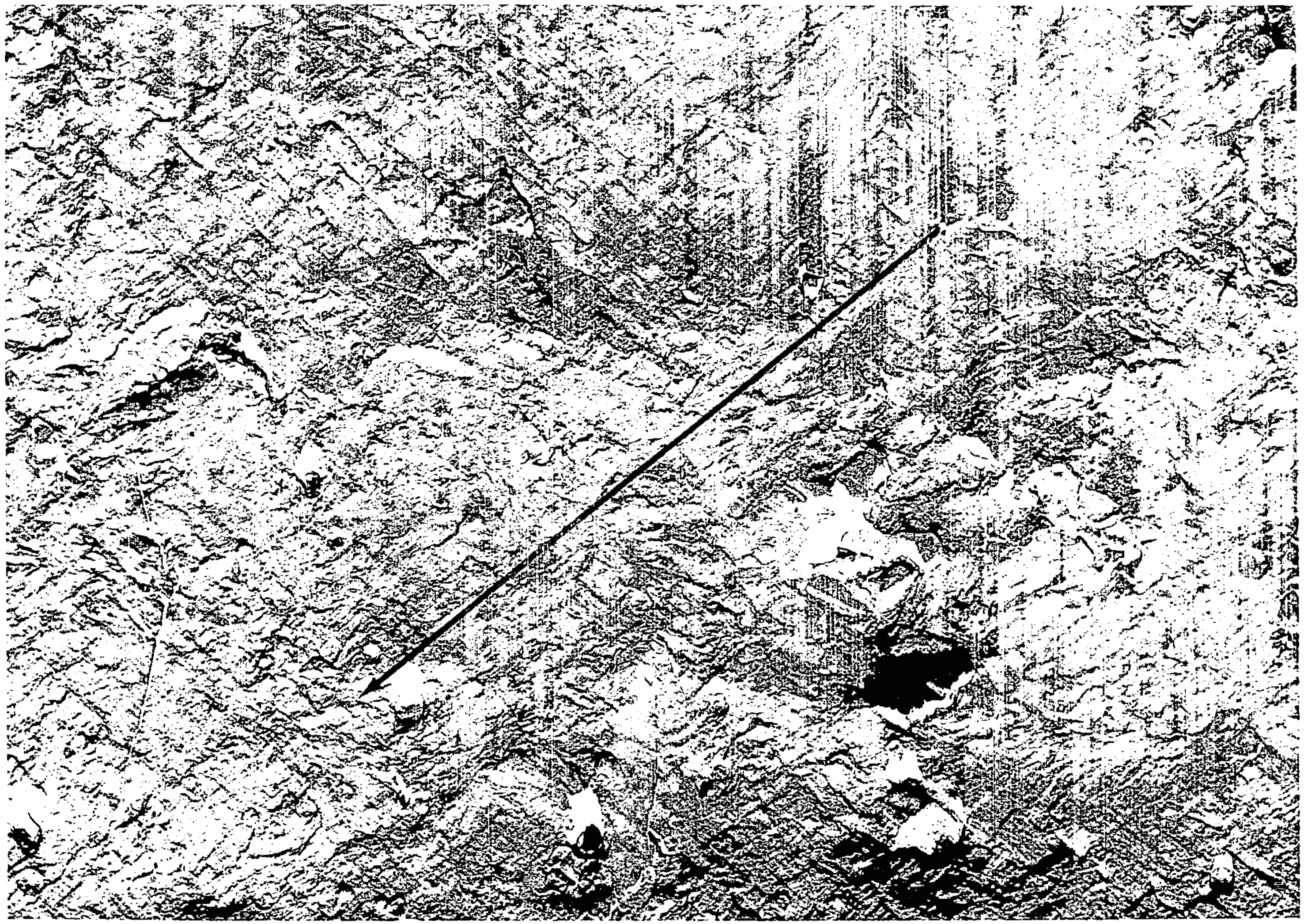


Figure 63 Example of Fatigue Striations Near Middle of Fatigue Crack of Fracture Surface A (Note evidence of Dual Load Levels) (Arrow Indicates Crack Direction) (X12,000)

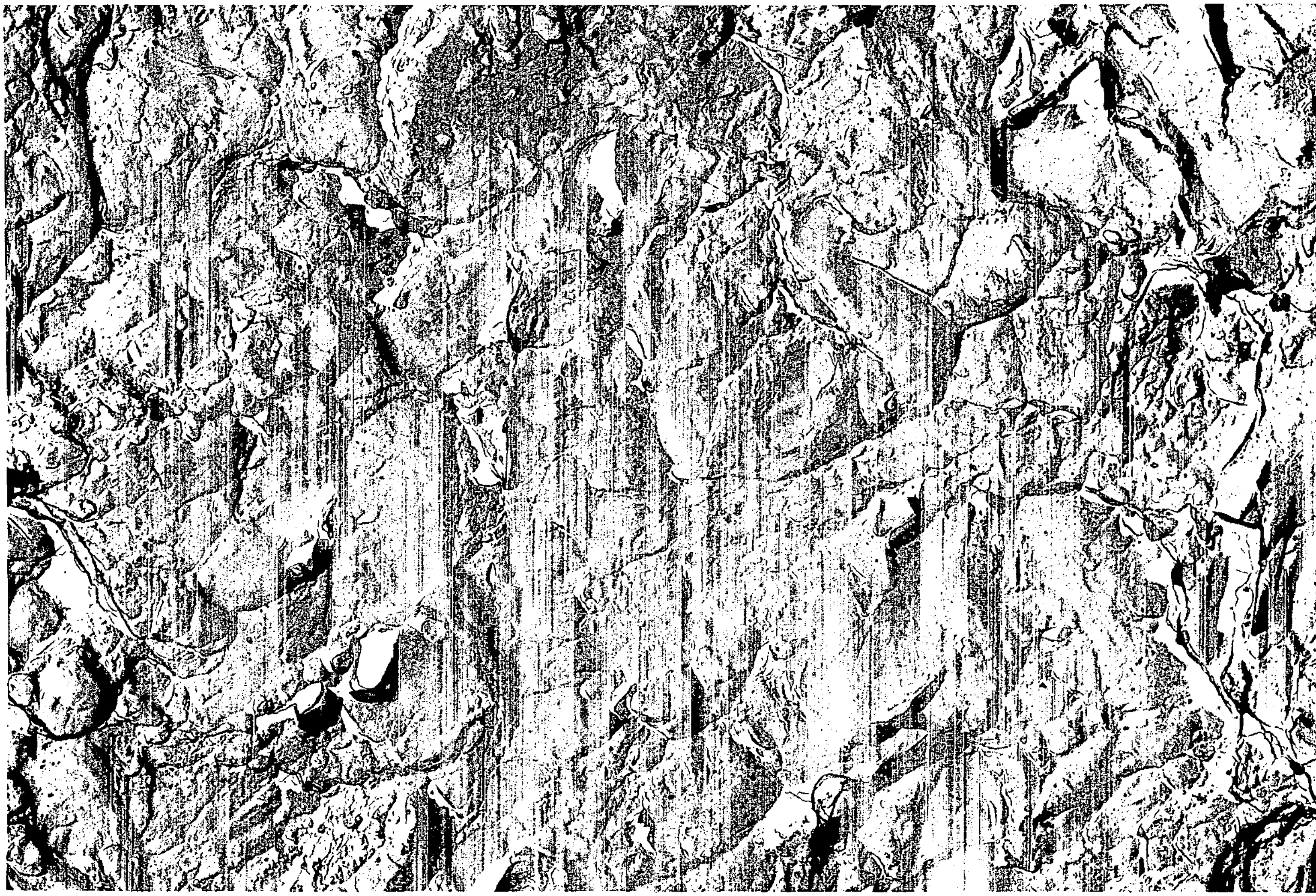


Figure 64   Example of Ductile Overload Found on Fracture Surface B   (X12,000)

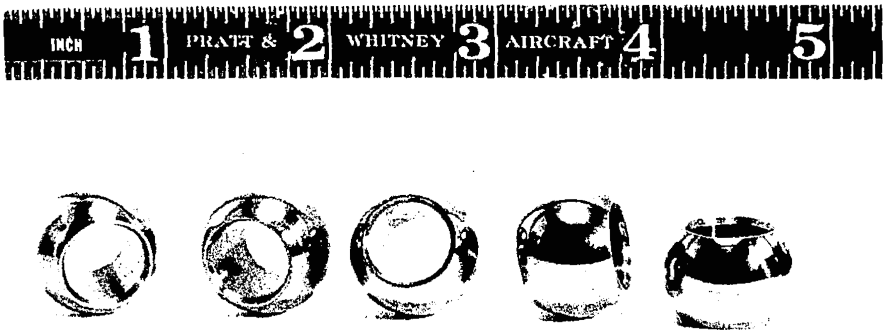


Figure 65 Appearance of Typical Intact Drilled Balls – Drilled-Ball Bearing S/N 2552A-2